Quantitative analysis of tooth wear *in-vivo* using 3D scanning technology

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Abstract

Aim: The primary aim of this study was to develop, calibrate and assess a novel methodology that employs 3D scanning technology in quantifying the progression of tooth wear and then assess the applicability and validity of this methodology *in-vivo* through clinical monitoring of the progression of tooth wear in patients over a period of 12 months.

Methods and materials: A Stainless Steel Model (SSM) was fabricated consisting of seven stainless-steel ball-bearings embedded in a horseshoe-shaped base. The dimensions of the SSM were ascertained using a Coordinate Measuring Machine (CMM). The CMM-calibrated SSM was used to identify the accuracy and precision of a contact stylus-profilometer scanner and a non-contact class-II laser arm-scanner. The next stage involved using the SSM to identify the initial dimensional accuracy of Type IV dental stone casts poured from impressions of the SSM, using 3 types of impression materials: alginates (Alg), polyethers (PE) and polyvinylsiloxanes (PVS), and the dimensional stability of the dental stone over a period of one-month. Thereafter, the overall 3D scanning system performance was calculated. A clinical study involving tooth wear patients, recruited through 3 Restorative Dentistry Consultants' New Patient clinics, was also carried-out. At initial visit and after 1 year, PE impressions were taken of participants' dentition and poured. At 1 month post-pouring, the casts were 3D-scanned. The resultant scans of initial-visit casts and after 1 year casts were 3D analysed, compared and differences detected.

Results: The contact scanner demonstrated greater accuracy and precision compared to the non-contact scanner. Alg-fabricated casts demonstrated the largest discrepancy, producing undersized casts. PVS was the most accurate but concurrently demonstrated greater statistical variance compared to PE. The overall 3D scanning system performance, when comparing 2 individual contact scans taken of Type IV stone casts poured from PE impressions then scanned at one-month post-pouring, was 66µm. Clinically, all participants in this study presented with tooth wear greater than 140µm in depth; however, detected tooth wear only affected a limited surface area of anterior teeth.

Conclusion: In this pilot study, we were able to formulate a novel descriptive 3D scanning methodology for quantifying tooth wear that accounts for the various factors affecting 3D scanning *in-vivo*. We have also demonstrated the clinical applicability of the methodology in monitoring the rate of tooth wear progression in patients.

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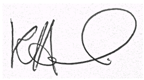
I dedicate this work to my Grandma, Reda. I am sorry I couldn't make it back in time.
I love you.

Author's Declaration

"I declare that, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at he University *of* Glasgow or any other institution."

Signature: 

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1. Introduction

Tooth wear, also referred to as tooth surface loss (TSL) or non-carious tooth surface loss, has been defined as the ‘pathological loss of tooth tissue by a disease process other than dental caries’ (Eccles, 1982). Originally, the term TSL was employed to distinguish between tooth surface sub-surface loss related to enamel caries. On the other hand, some argue the term has two main disadvantages (Smith et al., 1997). First, it understates the severity of tooth surface loss through implying that only one surface has been affected. The second disadvantage is its subtlety that might escape patients and dentists. Hence, tooth wear has been advocated as a more appropriate term to describe the loss of tooth surface (Smith et al., 1997).

The aetiological factors of tooth wear include attrition, erosion and/or abrasion. Attrition is tooth structure loss due to tooth-tooth contact. This includes tooth wear caused by certain para-functional habits such as bruxism that incorporates teeth grinding, and clenching (Pavone, 1985, Pintado et al., 1997, Kelleher and Bishop, 1999, Pergamalian et al., 2003, Van't Spijker et al., 2007, Lavigne et al., 2008, Arsecularatne and Hoffman, 2010). Erosion is tooth surface loss due to chemical/acid action from intrinsic and/or extrinsic factors and not involving bacteria. This may arise from factors including gastro-oesophageal reflux, a high intake of fizzy drinks, fruit juices or fruit consumption (Eccles and Jenkins, 1974, Eccles, 1979, Smith et al., 1997, Bartlett, 2006, Cochrane et al., 2009, Holbrook et al., 2009, Willershausen et al., 2009, Bartlett, 2010). In addition, abrasion is caused by physical wear from factors other than tooth-tooth contact for example tooth brushing, use of whitening/bleaching tooth paste, nail or pencil biting (Kelleher and Bishop, 1999, Bartlett and Dugmore, 2008, Turssi et al., 2010).

This chapter will review the contemporary body of research relating to the aetiology, mechanism, prevalence, assessment and management of tooth wear.

1.1 Thegosis, anthropology and tooth wear

Worn, flat occlusal surfaces and anterior edge to edge occlusion are common among dentitions of prehistoric man, where teeth were used as a third-hand, a tool or means of expressing aggression (Kaidonis, 2008, Lozano et al., 2008, Sato and Slavicek, 2008, Liu et al., 2010, Lorkiewicz, 2011).

A theory was proposed that man possesses an instinct to sharpen his teeth whenever under stress as a prime biological weapon (Every, 1965). Man's survival would depend on him being able to use his teeth as weapons to kill, tools to ingest or grasp, acquire language and socially interact. The primitive hominid, when threatened, would immediately extrude his mandible laterally and display his main weapon-his teeth- as a snarl. A display that still occurs in contemporary man during sleep as a repressed aggressive instinct (Every, 1960, Archer, 1988). A term was first used in 1970 to describe this behaviour of sharpening teeth, '*thegosis*' (from the Greek word *thego*- to whet or sharpen) (Every, 1970). This behaviour would be considered a normal physiological one, since the dentitions of ancient populations, were continually changing and compensating through attrition and tooth migration (Young, 1998, Kaidonis, 2008). Thegosis is instinctively inherited by contemporary man and with a recent reduction in wear severity, due to change in environment, resulted in failure to compensate and develop attritional occlusion (Scally, 1991). This leads to an increased frequency of various dental problems in modern societies that demonstrate a disparity between the original dentition design and our present environment (Kaifu, 2000, Kaifu et al., 2003).

On the other hand, Murray and Sanson, 1998, refuted the evidence for the existence of thegosis or the presence of ancestral genetic programming, stating that the evidence for thegosis was largely drawn from the behaviour of stressed animals, including man. They also stated that there is no evidence that any animal sharpens its teeth independently of the masticatory process in order to improve the efficiency of the process (Murray and Sanson, 1998). Scally (1999) published on the internet a rebuttal to Murray and Sanson, 1998, claiming the article did not review a number of critical references that directly addressed a number of issues raised in-regards to the theory of thegosis (http://www.8.co.nz/Thegotics/Murray_and_Sansons_Artricle_critical_review.htm#_Toc460653497).

1.2 Prevalence of tooth wear

A survey of 1007 patients established that 5.73% of tooth surfaces demonstrated unacceptable tooth wear for the 15-26 year-age group and 8.19% in the 56 – 65 year-age group (Smith and Robb, 1996). Another study examining 418 children with average age of 14 elucidated that 51% of study participants suffered from moderate erosion and only 1% had severe erosion (Al-Dlaigan et al., 2001a, Al-Dlaigan et al., 2001b). One of the largest prevalence tooth wear studies was the UK Child Dental Health Survey of 2003 (National Statistics: http://www.statistics.gov.uk/ssd/surveys/cdhs.asp). This identified that 53% of 5 year olds suffered from tooth wear with and 22% of them progressing into the dentine or pulp, demonstrating a rise in incidence of tooth wear compared to the 1993 survey. The Adult Health Survey of 2009 estimated that 77% of dentate adults in England, Wales and Northern Ireland, demonstrated signs of tooth wear extending to dentine in their anterior teeth, with prevalence of tooth wear increasing with age (White et al., 2011). The percentage of adults presenting with severe tooth wear increases from 3% at the age of twenty to 17% at the age of seventy. Indeed, increasing levels of tooth wear are significantly associated with age (Van't Spijker et al., 2009, Cunha-Cruz et al., 2010). Tooth wear has a measurable impact on patient satisfaction with their appearance, pain levels, oral comfort, general performance, chewing and eating capacity (Al-Omiri et al., 2006). The inconsistent use of various indices across tooth wear prevalence studies makes accurate comparisons between their results difficult (Bardsley, 2008, Curca and Danila, 2010).

1.3 Aetiology of tooth wear

The main aetiological factors behind tooth wear are erosion, attrition and abrasion. It is also generally accepted that tooth wear is multi-factorial, involving a number of aetiological factors that seldom happen in isolation and occur with different intensity and duration (Bartlett, 2005, Bartlett and Shah, 2006, Young et al., 2008). These aetiological factors include dental erosion, attrition, abrasion, non-carious cervical lesions or a combination of some or all of these factors.

1.3.1 Dental erosion

Dental erosion is defined as tooth surface loss of enamel and/or dentine resulting by chemical/acid action from intrinsic, extrinsic and/or environmental factors and not involving bacterial action (Eccles, 1979, Mair, 1992, Imfeld, 1996a, Bartlett, 2009).

Although the definition is universally accepted, some researchers focus on acidic erosion as the main aetiological factor behind tooth wear. Therefore, they use the term 'erosion' to refer to general tooth wear that encompasses erosion, attrition and abrasion (Bartlett and Dugmore, 2008, Bartlett, 2010). Others have suggested that the appropriate term to describe the condition should be corrosion rather than erosion (Michael et al., 2009). This is due to erosion being an abrasive process resulting from the dynamic contact of a solid, liquid or gas with a surface rather than static chemical action, as in the case of corrosion (Grippo and Simring, 1995).

1.3.1.1 Clinical appearance of dental erosion

Erosion lesions normally occur on smooth (facial, lingual and palatal), occlusal or incisal tooth surfaces of the teeth. This leads to the enamel surface having a silky-glazed appearance with loss of perikymata or developmental ridges. In more advanced cases, this result in formation of hollowed or cupped-out lesions with intact enamel along the gingival margin (figure 1.1). These hollowed lesions are most commonly found on the palatal surfaces of upper incisors and are historically termed perimolysis (Bartlett, 2005). In patients with severe dental erosion, the enamel may be completely removed. This leads to dentine exposure, leaving the tooth prone to sensitivity and further mechanical wear (figure 1.1). Uncontrolled advanced tooth wear may ultimately lead to pulpal exposure and requirement of root canal treatment or extraction (Lussi et al., 1991, Sivasithamparam et al., 2003, Lussi et al., 2006, Bartlett, 2007, Wiegand and Attin, 2007, Larson, 2009).

It is challenging to identify erosion based solely on clinical appearance, as the aetiology of the wear lesion is generally multi-factorial due to the interaction of erosion, attrition and abrasion (Bartlett et al., 1999, Bartlett, 2009, Young et al., 2008). To prevent further progression, it is important to detect this condition as early as possible (Lussi and Jaeggi, 2008).

1.3.1.2 Prevalence of dental erosion

Current scientific literature seems to report more frequently on the prevalence of dental erosion than on the prevalence of attrition and abrasion (Johansson et al., 2008). The majority of erosion prevalence studies in Europe and North America have involved children rather than adults (Bartlett, 2007). The 2003-2004 U.S National Health and Nutrition Examination Survey (NHANES) demonstrated that 45.9% of children aged 13 to 19 had evidence of erosive tooth wear affecting at least one tooth. A higher prevalence was established in males, Caucasians and over-weight children (McGuire et al., 2009).

A study involving 1,753 twelve year-olds residing in Leicestershire and Rutland (Dugmore and Rock, 2004b) identified that 59.7% of the children suffered from tooth erosion with 2.7% exhibiting deep lesions into exposed dentine. The study also reported a significantly higher prevalence of erosion in Caucasians compared to Asians. The results of this study agree with that of another which examined 418 fourteen year-olds in Birmingham (Al-Dlaigan et al., 2001b). The study identified that 51% of the 418 children assessed clinically suffered from moderate erosion and 1% had severe erosion with total loss of enamel and substantial loss of dentine. Both studies identified that erosion was more prevalent in males and those from lower socio-economic categories. Indeed, several studies have related tooth wear to people from lower socio-economic category (Milosevic et al., 1994, Jones and Nunn, 1995, De Carvalho Sales-Peres et al., 2008, El Aidi et al., 2008, El Aidi et al., 2010).

Another epidemiological study examined 2,351 fourteen year-olds in North West England (Bardsley et al., 2004). The relationship between the prevalence of erosion, water fluoridation and social deprivation was investigated. This study established that 53% of children had exposed dentine. Males were significantly more likely to have signs of tooth wear than females. Furthermore, there was a 30% reduction in erosion within children from fluoridated regions compared to non-fluoridated ones. In contrast to others, this study demonstrated that erosion was more prevalent in children from higher socio-economic categories. However, this is in agreement with results attained by (Millward et al., 1994).

An increase in the prevalence of erosion has been observed in children between 3.5 and 4.5 year olds. Moreover, children living in the North of the UK are twice as likely to suffer from erosion compared to those living in London and the South-East (Nunn et al., 2003).

The differences in obtained results between these studies examining the prevalence of erosion reflect the different definitions used in determining erosion, different wear indices employed, subjectivity of the indices, different geographical areas and population samples. A summary of the associations between tooth wear related to erosion and epidemiological factors is displayed in figure 1.1.

1.3.1.3 Mechanism of dental erosion

In-vitro studies have attempted to identify the actual mechanism by which acidic dissolution of the tooth surface occurs. Once the acidic solution is introduced in the oral environment it causes an immediate drop in the oral pH (Moazzez et al., 2000a). As acidic solution comes into contact with the tooth, it initially has to disperse through the acquired pellicle to engage the enamel surface. The acquired pellicle is a protein-based layer rapidly forming on dental surfaces post tooth brushing (Hannig and Balz, 1999). Thereafter, the hydrogen ion component of the acid starts to dissolve the enamel prism sheath and subsequently the prism core by attacking components of the hydroxyapatite, such as carbonate and phosphate. This results in a distinct honeycomb appearance (Meurman and Frank, 1991). Additional fresh, un-ionised acid then diffuses into the inter-prismatic areas of enamel and dissolve further mineral underneath the surface leading to an outflow of calcium ions termed demineralisation (Eisenburger et al., 2001, Lussi and Hellwig, 2001). Demineralisation of dentine follows a similar process. However, it differs by the presence of organic dentine matrix that hinders further diffusion of acid by buffering the acid. Once the dentine organic matrix starts degrading, the demineralization process progresses (Hara et al., 2005).

The tooth surface pH returns to above 5.5 within 2 minutes following acid exposure due to salivary buffering and clearance (Millward et al., 1997). It is also established that the un-stimulated salivary buffering capacity is lower in erosion patients compared to a healthy erosion free cohort (Meurman et al., 1994, Piangprach et al., 2009).

1.3.1.4 Aetiology of dental erosion

Historically, the causes of erosion have been classified into extrinsic or intrinsic sources (Eccles, 1979, Jarvinen et al., 1991). Alternatively, others have classified erosion into dietary, regurgitation and environmental (Smith and Knight, 1984b, Mair, 1992). Extrinsic erosion occurs if the source of acid is from outside the body. This is further sub-divided into dietary or industrial/environmental. A summary of the main aetilogical factors is demonstrated in Figure 1.1.

1.3.1.4.1 Dietary erosion

Dietary erosion is a result of food or drinks containing a variety of demineralising acids that are consumed in excess. It is considered by researchers to be the most common cause of acid erosion (Bartlett, 2009). The total titratable acid level of dietary substances, which measures the total available hydrogen ion concentration, is considered more important than their pH values (Jarvinen et al., 1991, Zero, 1996, Cochrane et al., 2009).

1.3.1.4.1.1 Carbonated drinks

Carbonated drinks have been directly related to erosion as they contain a variety of acids capable of chelating as well as dissolving calcium ions. The effect is more determined when consumption occurs on a daily basis (Jarvinen et al., 1991, Milosevic et al., 1997, Kelleher and Bishop, 1999, Moazzez et al., 2000b, Waterhouse et al., 2008).

A study involving 418 fourteen year old children residing in Birmingham (Al-Dlaigan et al., 2001b) determined that 23% of the study participants had more than 22 intakes per week of Cola and other carbonated drinks. It was concluded that there was a relationship between dental erosion and acidic dietary intake. Dugmore and Rock (2004a) examined 1,753 children at the age of twelve then re-examined at the age of fourteen The children were also asked to complete questionnaires related to their dietary habits on both occasions. The study identified a significant association between tooth erosion and the amount and frequency of carbonated drinks intake. Fourteen year-olds were 10 times more likely to have tooth erosion if drinking carbonated drinks four or more times each day with a confidence interval of 95%. These results were further reinforced by a review based on cross-sectional prevalence studies from the 1993 UK children's' dental health survey and the dental report of 2 National Diet and Nutrition Surveys of children aged 1.5 – 18 years old (Nunn et al., 2003). The review identified a trend towards a higher prevalence of erosion in children who consumed carbonated drinks on most days compared to infants consuming carbonated drinks less frequently. Furthermore, not only the frequency of consumption of carbonated drinks but also their pattern of consumption has a direct relation to the susceptibility to erosion. A significantly higher prevalence of erosion was observed in children who drank twice as quickly as well as those who drank straight from the can (Moazzez et al., 2000a).

The erosive potential of 15 drinks was analysed by measuring *in-vitro* the weight loss, surface loss and release of calcium ions from human enamel following 30-minute or 24 –hour exposure using white-light non-contact surface profilometry (Cochrane et al., 2009). The study concluded that Pepsi™ and Coca-Cola™ demonstrated the highest erosive potential of all 15 beverages tested according to all three measurements (Table 1.1). The erosive potential of carbonated drinks was further confirmed by a study that compared beverages available in U.K and the U.S.A (Murrell et al., 2010). Extracted, caries-free molars and premolars were submerged into different beverages for 25 hours. They were then examined using a polarized light microscope and enamel lesions were identified and measured. The results of the study elucidated that U.K Diet Coke™, Sprite™ and Sprite Zero™ produced deeper lesions when compared to their U.S counterparts. These results demonstrate that these UK carbonated drinks were more erosive. Sprite Lite™ was also found to cause the highest significant decrease in enamel micro-hardness when compared to grapefruit and apple juice (Lussi et al., 1993).

1.3.1.4.1.2 Fruits and fruit juice consumption

Fruits and fruit juices are potentially one of the factors leading to tooth erosion (Eccles and Jenkins, 1974, Lussi et al., 1991, Zero, 1996). Citrus fruits, apples, cranberries and grapes are considered to possess a high erosive potential especially when eaten more than twice a day (Jarvinen et al., 1991, Lussi et al., 1993, Lussi and Hellwig, 2001, Sirimaharaj et al., 2002, Bartlett, 2005). A single centre, randomised, placebo controlled, blind, crossover design study examined ten subjects, each consuming 11 servings of orange juice per day for 15 days (West et al., 1998). The study demonstrated a significant relationship between orange juice intake and incidence of tooth erosion. Furthermore, drinking habits prior to swallowing, such as swishing, sucking or holding fruits and/or fruit juices were associated with an increased risk of erosion (O'Sullivan and Curzon, 2000). The results of these studies were confirmed by an epidemiological study that demonstrated an association between fruit intake and erosion (Al-Dlaigan et al., 2001a). The study also identified that approximately 10% of the 418 fourteen year-old children examined had a medium to high intake of fruits. Female adolescents in particular had a greater fruit intake when compared to their male counterparts.

1.3.1.4.1.3 Alcohol consumption

Alcohol abuse has been associated with tooth erosion (Robb and Smith, 1990). A study demonstrated that 49.4% of alcoholics undergoing rehabilitation suffered from enamel and/or dentine erosion lesions (Manarte et al., 2009b). White wines have been found to be more erosive than red wines causing up to 60μm demineralisation of enamel after 1400 one-minute exposures to wine (Ferguson et al., 1996, Chaudhry et al., 1997, Mok et al., 2001, Willershausen et al., 2009). Gastritis and acid regurgitation are also common complications of chronic alcoholism (Simmons and Thompson, 1987)

1.3.1.4.1.4 Other food items

A number of food items have also been implicated in causing erosive tooth wear. Fruit flavoured and Cola flavoured lollipops (Brand et al., 2009), candy sprays (Gambon et al., 2009), alcopops (Ablal et al., 2009), a lacto-vegetarian diet (Linkosalo and Markkanen, 1985, Linkosalo, 1988), herbal tea (Phelan and Rees, 2003), flavoured sparkling water (Parry et al., 2001, Brown et al., 2007) as well as sour sweets and candies (Davies et al., 2008, Wagoner et al., 2009), have all been found to have an erosive potential.

Dietary acids cause an immediate drop in oral pH. Thereafter the saliva neutralises it and returns the oral pH to 7 within a couple of minutes. A low pH of 3 has been found to cause rapid enamel wear. This enamel wear was even more rapid than that observed in other restorative materials present in a similar pH value environment (Richards et al., 2010). Hence, the important factor in dietary erosion is frequency of intake along with any eating habits (Bartlett, 2009). Several authors have suggested that using a straw is beneficial in decreasing the erosive effect of various erosive drinks (Grobler et al., 1985, Imfeld, 1996b, Edwards et al., 1998). Other studies have shown that the addition of calcium to various drinks reduced their erosive potential on enamel significantly (West et al., 2003, Hooper et al., 2004a).

1.3.1.4.2 Industrial/environmental erosion

Industrial erosion is caused by exposure to various types of acidic contaminants in the workplace such as chemicals, petrochemicals, metals, semiconductors and airborne dust (Elsbury et al., 1951, Skogedal et al., 1977, Malcolm and Paul, 1961, Enbom et al., 1986, Petersen and Henmar, 1988, Petersen and Gormsen, 1991, Tuominen et al., 1991, Amin et al., 2001, Kim and Douglass, 2003, Johansson et al., 2005, Jokstad et al., 2005, Cope and Dupras, 2009).

A systematic review of 42 studies addressing industrial erosion concluded that battery and galvanising workers were at highest risk of dental erosion (Wiegand and Attin, 2007). Differences in study design and lack of existing randomised case-control studies do not allow for statistical analysis. The review concluded that the risk of erosion as well as its severity increases with increasing concentration of the acid or increasing exposure time.

Although limited evidence exists, there seems to be an association between tooth erosion and swimming. An epidemiological survey reported that 12% of swimmers and 39% of swim team members suffer from dental erosion (Centerwall et al., 1986). Other studies have also agreed with these findings and concluded that the cause of erosion was the low pH gas-chlorinated pool water (Geurtsen, 2000).

1.3.1.4.3 Drug-related erosion

Various drugs have been associated with tooth erosion. Aspirin possesses an erosive potential slightly lower than citric acid, especially if chewed or not buffered (Hannig et al., 1992, Rogalla et al., 1992, Grace et al., 2004, McNally et al., 2006). Anti-asthmatic drugs in the powder form such as beclomethasone diproprionate, fluticasone, salmeterol and terbutaline sulphate have a pH lower than 5.5 and are more acidic than aerosol versions. Hence, patients prescribed these drugs are at a risk of developing tooth erosion (O'Sullivan and Curzon, 1998). Asthmatic patients are also prone to developing gastroesophageal reflux disorder (GORD) (Stordal et al., 2006). Furthermore, effervescent vitamin-C has also been associated with erosion (Meurman and Murtomaa, 1986).

Other drugs have been found to cause xerostomia, which leads to the impairment of the buffering capability of the saliva to acidic exposure (Fox et al., 1985). The most commonly implicated drugs are: alpha receptor antagonists, anticholinergics, radioiodine, atropinics, muscarinic receptor antagonists, HIV protease inhibitors, antidepressants and antipsychotics (Friedlander and Mahler, 2001, Scully, 2003, Al-Hiyasat et al., 2006, Tschoppe et al., 2010).

1.3.1.4.3.1 Ecstasy

Less commonly known as 3,4-methylenedioxymethamphetamine (MDMA) is a highly addictive powerful stimulant (Hamamoto and Rhodus, 2009). Ecstasy users suffer from xerostomia which prevents the salivary buffering and clearance of any dietary acids (Dicugno et al., 1981, Duxbury, 1993). Furthermore, Milosevic et al.,(1999) reported that 93% of ecstasy users consumed a mean of three cans of carbonated drinks per ‘trip’. Another study identified that out of 3,503 study participants, 66% reported consuming alcohol in combination with ecstasy (Tossmann et al., 2001). As a compounding factor, ecstasy users frequently report jaw clenching and teeth grinding during ecstasy use (Cohen, 1995, Harris et al., 2002, McGrath and Chan, 2005). A study reported that 60% of ecstasy users suffered from advanced tooth wear extending into the dentine compared to 11% of non-users. Also, the route of administration had a significant association with severity of tooth wear with snorting methamphetamine causing the highest anterior tooth wear (Richards and Brofeldt, 2000). Dopaminergic, serotonergic and adrenergic system affecting drugs have been found to exacerbate bruxist activity in humans (Winocur et al., 2003).

1.3.1.4.3.2 Oral care products

Some oral care products, including fluoride-free toothpastes as well as some mouthwashes have also demonstrated an erosive potential through the reduction in enamel surface micro-hardness (Lussi and Hellwig, 2001, Pontefract et al., 2001, Pretty et al., 2003).

1.3.1.4.4 Gastroesophageal reflux disease (GORD/GERD)

GORD/GERD is defined by the Montreal evidence-based consensus as a condition that develops when the reflux of stomach contents causes troublesome symptoms and/or complications. The characteristic symptoms of GORD include heartburn, regurgitation and chest pain resembling ischemic cardiac pain (Vakil et al., 2006). GORD is a common condition with a prevalence that varies in different parts of the world. 20-30% of the population in Western Europe and North America have been diagnosed with GORD (Stanghellini, 1999, Tougas et al., 1999, Dent et al., 2005).

GORD is often first diagnosed by dentists through observation of its oral manifestations (Barron et al., 2003, Holbrook et al., 2009). Gastric refluxate has a pH of less than 2.0 and thus has the potential to cause dental erosion (Lazarchik and Filler, 2000). A systematic review was carried out to review the existing literature assessing the relationship between GORD and dental erosion (Pace et al., 2008). Seventeen studies fulfilled the selection criteria. The review concluded that there was a large variance in the prevalence of dental erosion in GORD. Dental erosion was present in 5 – 47.5% of GORD patients. Alternatively, 21 – 83% of dental erosion patients suffered from GORD. Furthermore, a controlled descriptive study and double-blind placebo-controlled clinical study concluded that nocturnal bruxism might be secondary to nocturnal GORD, occurring via sleep arousal and often together with swallowing (Miyawaki et al., 2003). Rhythmic masticatory muscle activity and clenching episodes were also found to be significantly higher during decreased esophageal pH episodes especially during supine position (Miyawaki et al., 2004).

1.3.1.4.5 Eating disorders

Eating disorders include anorexia nervosa, bulimia and rumination. Eating disorders have been associated with tooth erosion. They are a group of psychopathological disorders affecting patient relationship with food and his/her own body. This is manifested through distorted or chaotic eating behaviour (Lo Russo et al., 2008). Teenage females are particularly prone to eating disorders (O'Sullivan and Milosevic, 2008).

Dental erosion can be frequently encountered in eating disorders' patients. It is estimated that between 35 – 38% of eating disorder patients suffer from tooth erosion (Simmons et al., 1986, Roberts and Li, 1987). This is particularly evident on the palatal surfaces of anterior and posterior teeth (Jarvinen et al., 1992, Chadwick and Mitchell, 2001). This could be caused by purging behaviour of gastric acidic contents (Hellstrom, 1977, Hurst et al., 1977) or elevated consumption of carbonated drinks to boost energy (O'Sullivan and Curzon, 2000) or to decrease the reflex hunger stimulus (Moazzez et al., 2000a, Al-Dlaigan et al., 2001a).

Hypersalivation occurs in advance of vomiting, as frequently seen in individuals suffering from voluntary regurgitation such as anorexia nervosa, bulimia nervosa and rumination (Lee and Linden, 1992). On the other hand, GORD patients do not possess this protective mechanism prior to gastric refluxation as this is an involuntary action. Hence, no increase in salivary output is present to counter-balance the gastric refluxate (Saksena R et al., 1999).

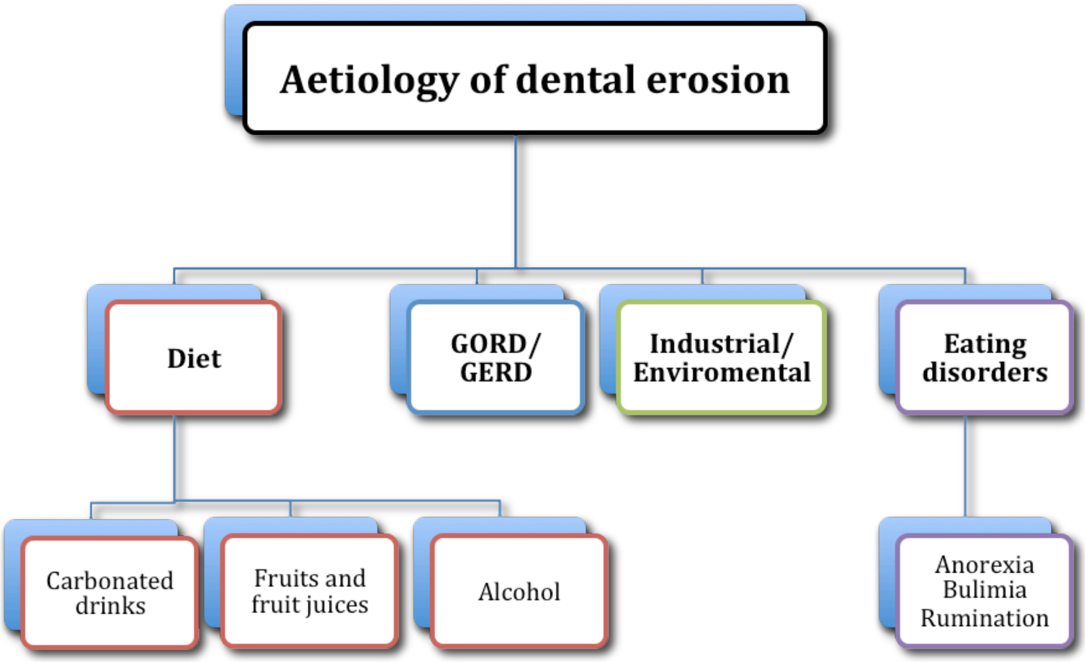


Figure 1.1: Summary of the main aetiological factors of dental erosion based on source of erosive element, whether intrinsic or extrinsic.

Table 1.1: The effect of carbonated/ fizzy drinks on dental enamel. The erosive potential of 6 out of 15 drinks analysed by measuring *in-vitro* pH, weight loss (WL), surface loss (SL) and release of calcium ions ΔCa from human enamel using white-light non-contact surface profilometry. Adapted from Cochrane *et al.*, 2009

Beverage	pH (initial)	pH (decarbonated)	WL (mg/mm^2)	SL (µm)	ΔCa ($\mu mol/mm^2$)
Coca-Cola	2.39	2.86	0.79±0.13	7.04±0.29	10.89±1.89
Pepsi	2.36	2.78	0.73±0.10	7.07±1.28	10.44±1.94
Pepsi Max	2.79	3.07	0.51±0.05	4.64±2.18	6.90±0.47
Coca-Cola Zero	2.97	3.21	0.39±0.10	5.84±0.95	5.34±1.44
Sprite	3.02	3.23	0.31±0.05	2.39±0.70	4.97±0.55
Diet Coca-Cola	3.05	3.30	0.30±0.00	4.20±1.33	4.14±0.44

1.3.2 Attrition

Attrition is defined as the loss of tooth tissue/tooth wear due to friction between opposing teeth. Hence, attrition is considered as a direct resultant of occlusion (Van't Spijker et al., 2007).

1.3.2.1 Aetiology of attrition

Attrition is associated with para-functional oromandibular or lingual activities that may include, alone or in combination: jaw clenching, bruxism, tooth grinding, tooth tapping, cheek, lip or tongue biting, tongue pushing against teeth, licking lips, tongue protrusion, gum chewing, object biting, hypersalivation/swallowing, backward or forward or lateral head or jaw posturing (Kampe et al., 1996, Winocur et al., 2001, Kato et al., 2003, Lavigne et al., 2008).

Attrition is one of the main signs of bruxism, with tooth wear progressing faster in bruxers than in non-bruxers from a study observing 15 patients (Xhonga, 1977). The hypothesis was that grinding forces are extremely destructive due to their lateral rather than occlussal direction (Nadler, 1966). Tsiggos et al. (2008) examined 180 participants and classified them into 2 groups (50 self-reported bruxers and 52 non-bruxers) based-on 2 questionnaires regarding grinding and/or clenching of their teeth (Tsiggos et al., 2008). Anterior or posterior dental attrition was assessed by two calibrated examiners on diagnostic casts. Results of the study demonstrated there was a significant association between self-reported bruxism and attrition. The study concluded that signs of dental attrition might help differentiate self-reported bruxers from non-bruxer subjects.

However, more recent studies seem to demonstrate that the assumed relationship between attrition and bruxism should be taken with caution. Eighty-four participants previously diagnosed with TMD, based on the Research Diagnostic Criteria for TMD, were examined in a study aimed at identifying the association between wear facets, bruxism and severity of facial pain in TMD patients (Pergamalian et al., 2003). Tooth wear facets on mandibular casts were measured using a 4-point scale by one calibrated examiner. Bruxism was assessed using a standardised pre-treatment questionnaire. The study concluded that there was no significant association between bruxism, TMJ pain or muscle pain and tooth wear. Another study investigated the use of tooth wear as a discriminator between sleep bruxers and controls in 130 participants (Abe et al., 2009). The study concluded that although tooth wear discriminates between sleep bruxers with a current history of tooth grinding from non-bruxers, its diagnostic value is modest as it failed to discriminate the severity of sleep bruxism.

A systematic review of 33 studies concluded that attrition seems to co-exist with self-reported bruxism (Van't Spijker et al., 2007). However, since all previous associations between attrition and bruxism were based on self-reported bruxism, such associations might not be reliable as many patients might not be aware of their bruxing behaviour (Lavigne et al., 1996).

1.3.2.1.1 Bruxism

The term 'la bruxomanie' was first coined by Marie Pietkiewicz in 1907 (Pietkiewicz, 1907). Bruxism is a stereotyped oral motor disorder, characterised by teeth grinding and clenching during sleep as well as during wakefulness (ICSD, 2005, Lobbezoo et al., 2006). The bruxing movement usually occurs without patient awareness through rhythmic or sustained-tonic contractions of the masseter and other jaw muscles (Bader and Lavigne, 2000).

A host of dental problems have been associated with bruxism. These include attrition such as mechanical wear, resulting from para-function, and limited to the contacting surfaces of the teeth (Xhonga, 1977), hypertrophied masticatory muscles (Svensson et al., 2001, Farella et al., 2010) , fractures ⁄ failures of restorations or dental implants (Lobbezoo et al., 2006) or headache and temporomandibular disorder pain in the masticatory system (TMD pain)(Glaros et al., 1998, Michelotti et al., 2010, Manfredini and Lobbezoo, 2010).

1.3.2.1.1.1 Risk factors of bruxism

There are a number of risk factors associated with bruxism, including: TMD, dental erosion, smoking, anxiety and stress. Other less established correlations have been associated between bruxism and genetics (Horowitz, 1963, Lindqvis.B, 1974), drugs (Winocur et al., 2003) and respiratory disturbances (Gold et al., 2003).

Bruxism and TMDs

Trempromandibular disorders (TMD) is a collective term that describes a number of clinical complaints involving the muscles of mastication, trempromandibular joints and associated orofacial structures (Glaros and Burton, 2004, Johansson et al., 2004).

A study examined the relationship between the frequency of sleep bruxism and TMD on 195 participants using a BiteStrip®. The BiteStrip® (www.bitestrip.com) was used to indicate the total sleep bruxism events per night on a 4-grade score (Nagamatsu-Sakaguchi et al., 2008). The study demonstrated that there was a significant relationship between the presence of TMJ clicking and severe bruxism. This comes in agreement with the findings of another study examining the association between para-functions (diurnal clenching and/or grinding and nail-biting) and TMDs (Michelotti et al., 2010). Results demonstrated that daytime clenching/grinding was a significant risk factor for myofascial pain, with females more prone to it than males.

On the other hand, a study was carried out on 646 participants, aged 35-44. The aim of the study was to examine the association between self-reported TMD pain and anterior tooth wear as an indicator for long-term bruxing behaviour (Schierz et al., 2007). The study concluded that a clinically relevant dose-response relationship does not appear to exist. A systematic review of the literature between 1998 to 2008 examined forty six articles and concluded that studies that used more quantitative and specific methods to diagnose bruxism, rather than self-reporting, demonstrated a much lower association between bruxism and TMD (Manfredini and Lobbezoo, 2010).

Bruxism and erosion

A number of studies have reported an association between GORD/GERD and nocturnal/sleep bruxism (Miyawaki et al., 2003, Miyawaki et al., 2004, Gharaibeh et al., 2010). The association between nocturnal bruxism and GORD/GERD was examined in a study involving 10 bruxers and 10 non-bruxers matched for height, weight, age and sex (Miyawaki et al., 2003). Bruxers demonstrated a significantly higher frequency of nocturnal rhythmic masticatory muscle activity episodes, and a higher frequency and percentage of time of gastroesophygeal reflux episodes when compared to non-bruxers. Another study concluded that clenching episodes occurred in-relation to gastroesophygeal reflux especially in supine position (Miyawaki et al., 2004). One hundred and four patients suffering from excessive tooth wear from South-East Queensland were divided into bruxers, non-bruxers and possible bruxers (Khan et al., 1998). The presence of occlussal attrition or erosion was identified using epoxy resin dental casts scanned using an electron microscope. The study compared the incidence of erosion versus attrition across all three groups. Results of the study demonstrated that erosion existed in all sextants in all 3 groups. The only exception was the mandibular anterior sextant where attrition was noted more often in bruxers. The study concluded that even if the patient is suspected of having bruxism, dental erosion is more likely to be the cause of the observed tooth wear.

Bruxism and smoking

There is evidence to show an association between bruxing and smoking. A nationwide survey of two thousand and nineteen Canadians examining the relationship between restless legs syndrome, sleep bruxism and smoking demonstrated a trend between self-reported bruxism and smoking (*p=0.056)* (Lavigne et al., 1997). A nationwide Finnish twin cohort study of 3,124 participants concluded that weekly bruxers were more than 2 times more likely to report heavy smoking than non-bruxers (Rintakoski et al., 2010b). A 24-month follow-up study of 205 participants classified into bruxers and controls observed that smokers were 2.4 times as likely to report frequent bruxism compared to non-smokers (Nunn, 2005).

Bruxism and anxiety/stress

A cross-sectional telephone survey of 13,057 participants in the United Kingdom, Germany and Italy was aimed at identifying the risk factors associated with sleep bruxism (Ohayon et al., 2001). The study reported an 8.2% prevalence of participants grinding their teeth at least weekly. The results also demonstrated that participants suffering from anxiety, stress, smoking, heavy alcohol drinkers, loud snoring and caffeine were all at a higher risk of reporting sleep bruxism. Another study involved 1,784 participants, aged between 30 to 55 years, attempted to examine the relationship between reported bruxism and stress experience using questionnaires (Ahlberg et al., 2002). The study demonstrated a significantly positive association between bruxism and severe stress experiences. This is in agreement with Giraki et al. (2010) who observed the correlation between stress and sleep bruxism in sixty nine participants (Giraki et al., 2010). The study used questionnaires and a Bruxocore-Bruxism-Monitoring device. The study concluded that participants with high sleep bruxism activity tend to feel more stressed at work and in their daily life.

1.3.2.1.2 Physiological attrition

Some investigators have argued that attrition is a part of the normal ageing physiological process rather than a pathological condition requiring intervention (Berry and Poole, 1974). They hypothesised through comparison with other mammals, in-particular herbivores, that humans have an adapting mechanism to compensate for the tooth wear. This mechanism involves the deposition of secondary dentine, alveolar growth and muscle adaptation. Berry and Pole concluded that because of this compensation mechanism, then attrition, whatever its extent, can never be excessive. Although some anthropological evidence seem to support this theory (Johansson et al., 2008, Forshaw, 2009), the hypothesis remains unproven (Bartlett and Dugmore, 2008).

Attrition has been observed in all age groups (Smith and Robb, 1996, Khan et al., 1998, Strausz et al., 2010). However, the decision on whether the observed attrition is pathological or age-related seems to depend on the clinical judgement of the assessor. This arises from the absence of a scientific, defined and reproducible threshold that distinguishes between physiological and pathological patterns of wear. State health care authorities, private insurance schemes, industry, dentists and patients all have different interpretations on what is pathological and what is not (Bartlett and Dugmore, 2008, Koyano et al., 2008).

Further detrimental effects of attrition on the dentition include loss of occlusal vertical dimension (Owen et al., 1991), loss of essential tooth morphology and change in masticatory efficiency (Luke and Lucas, 1983), tooth mobility (Pavone, 1985) breach of occlusal enamel, dentine exposure and pulpal involvement (Ingle, 1960, Tronstad and Langelan, 1971).

1.3.2.2 Clinical appearance of attrition

The appearance of atypical facets (bruxofacets) on the teeth remains one of the main clinical signs of attrition. These facets are flat, smooth, shiny areas with sharp well-defined edges that correspond with the antagonist tooth when the mandible is moved more than 3.5mm from centric occlusion in a lateral excursion (Lindqvis.B, 1974, Khan et al., 1998). The wear generally occurs on the incisal edges of the anterior teeth and on the cusps and restorations of the posterior teeth (Glaros and Rao, 1977, Kelleher and Bishop, 1999).

Other non-tooth-related signs are tongue indentations and linea-alba on the buccal mucosa due to tongue thrusting and cheek-biting concomitant with bruxism (Wiktorsson et al., 1997).

1.3.3 Abrasion

Abrasion is defined as the pathological wearing of dental hard tissue through mechanical forces by repeated introduction of foreign bodies into the oral cavity, which are in contact with the teeth (Levitch et al., 1994, Imfeld, 1996a). If the teeth are worn by friction from the food bolus forced by the tongue, lips and cheeks during mastication, this wear is then termed ''masticatory abrasion''(Grippo et al., 2004).

1.3.3.1 Clinical appearance of abrasion

Abrasion has been associated with non-carious cervical lesions and considered as one of their aetiological factors. These lesions are more common on the buccal surfaces of upper and lower anterior teeth and lower posterior teeth (Khan et al., 1999). Abrasion lesions tend to be wedge-shaped, located at the cement-enamel junction, free of plaque and not discoloured (Levitch et al., 1994). On the other hand, other *in-vitro* studies were able to create non-carious cervical lesions of varying shapes, sizes and surface textures (flat, cup-shaped, smooth and striated) through tooth brushing with toothpaste being the sole aetiological factor (Dzakovich and Oslak, 2008). The study demonstrated that attempting to identify aetiology of non-carious cervical lesion based only on clinical appearance could be challenging. Furthermore, abrasion lesions could be present on the incisal and occlusal surfaces of teeth if caused by certain para-functional or occupational habits (Jokstad et al., 2005, Barbour and Rees, 2006).

1.3.3.2 Aetiology of abrasion

There are a number of aetiological factors associated with abrasion. The most common factors relate to oral hygiene care, mainly tooth brushing and the use of dentifrices.

Abrasion can also occur due to certain habits, such as: pipe smoking, improper use of dental floss and toothpicks, chewing tobacco, biting pencils, pens and finger-nails (Faulkner, 1990, Gupta, 1990). Partial-denture clasps tend to abrade hard-tissue of abutment teeth (Ahmad et al., 1992). Occupational abrasion was also noted amongst tailors; shoemakers, glassblowers and wind-instrument musicians who tend to use their teeth in their occupations (Gupta, 1990, Prpić-Mehicić G, 1998, Kovacevic and Belojevic, 2006).

1.3.3.2.1 Abrasion and tooth brushing

A study examined the brushing habits of 103 participants in Giessen/Germany (Ganss et al., 2009) and evaluated the frequency, duration, technique and force of brushing. The results of the study demonstrated that 22% of the participants used horizontal tooth brushing movements. Horizontal brushing has been proven to cause 2 to 3 times as much tooth wear when compared to vertical brushing (Sangnes, 1976). Studies have demonstrated that normal tooth brushing alone does not cause any significant enamel wear and only minute dentine wear being restricted to the smear layer (Manly et al., 1965, Absi et al., 1992).

Whitening toothpastes contain particles know as abrasives. These abrasives are insoluble components added to toothpaste to aid in stain-removal. These abrasives include hydrated silica, calcium carbonate, dicalcium phosphate dehydrate, calcium pyrophosphate, alumina, perlite and sodium bicarbonate (Hefferren, 1998). The abrasive wear rate/relative dentine abrasivity (RDA) increases linearly as the abrasive particle size increases (De Boer et al., 1985, Macdonald et al., 2010).

A systematic review of 35 publications, through a meta-analysis, found no difference in safety of oscillating-rotating powered brushes when compared to manual toothbrushes in sound enamel and dentine (Van der Weijden et al., 2011). The review concluded that oscillating-rotating powered toothbrushes do not pose a clinically relevant concern to hard or soft tissues.

1.3.3.2.2 Abrasion and erosion

A single-blinded, randomized, cross-over design study involving fifteen participants aimed at examining the interplay between abrasion and erosion in enamel and dentine (Hooper et al., 2003). Over a 10-day period, participants wore an upper removable acrylic appliance between 0900 and 1700. The appliance contained one polished enamel and one polished dentine specimen. The specimens were then exposed to one of five regimes: drinking water and brushing with one of two toothpastes, drinking orange juice or drinking orange juice and brushing with one of two toothpastes. Drinking and brushing times were regulated and measurement of tissue loss was made on day 5 and day 10 using a profilometer. The study demonstrated that dentine wore more than enamel across all regimes. For enamel, there was significant tooth wear with orange juice and brushing, but no significant difference with brushing alone. For dentine, many specimens demonstrated tooth wear that exceeded the profilometer's 50μm limit. Dentine tooth wear was significant across all regimes.

Brushing of demineralised dentine with a load exceeding 4 newton produced 225–462 nm of tooth wear (Wiegand et al., 2007). The use of rotating, oscillating, sonic, or ultrasonic brushing action was associated with mineral loss of eroded dentine ranging between 9.94–16.45 μm after exposure to 20 brushing cycles, 30 seconds each, after demineralisation with 1% citric acid and remineralisation with artificial saliva (Wiegand et al., 2006). Toothbrushes with 0.2 mm filament diameter caused higher eroded enamel loss than 0.15 and 0.25 mm filaments (Wiegand et al., 2008). Furthermore, there are conflicting results in regards to the abrasiveness of different types of toothbrushes and their ability to carry toothpaste. Some studies demonstrated that soft toothbrushes caused more tooth wear than harder ones (Dyer et al., 2000). DeBoer at al., (1985) demonstrated that moderate toothbrushes caused more tooth wear. While Veronets el al., (2008) demonstrated no difference between the abrasivity of soft and hard tooth brushes.

A synergistic mechanism seems to exist between erosion and abrasion. Acidic exposure leads to demineralisation of hard tissues, resulting in a decrease in surface hardness and creating a surface that is more susceptible to physical impacts (Lussi and Jaeggi, 2008). A thirty-minute interval between an erosive exposure and tooth brushing grants dentin protection from further tooth wear through salivary buffering and smear layer reformation (Attin et al., 2004, Dawes, 2008, Joiner et al., 2008). Furthermore, Absi et al., (1992) advocated that dentists should consider advising their patients to brush their teeth prior to eating. This is due to the reformation of the smear layer post-tooth brushing that provides protection against acidic exposure (Absi et al., 1992).

A number of abrasion studies tend to exaggerate clinical conditions intentionally. These studies often produce a higher amount of wear than in the clinical situation, especially as modifying biological factors such as salivary buffering and pellicle protection, are not simulated adequately (Wiegand and Attin, 2011).

1.3.4 Non-Carious Cervical Lesions

Non-carious cervical lesions (NCCLs) are defined as the loss of hard-tissue tooth substance at the cement-enamel junction through processes unrelated to caries (Bader et al., 1993, Mair, 1992, Levitch et al., 1994). Other terms used to describe the lesions are ‘cervical erosion/abrasion’ lesions and abfractions (Bartlett and Shah, 2006). NCCLs may lead to tooth sensitivity, increased plaque retention, poor aesthetics and compromised pulp vitality (Michael et al., 2010).

1.3.4.1 Clinical Appearance of NCCLs

NCCLs occur in various forms and on different tooth surfaces. The most characteristic form is the angular V or wedge-shaped lesion when viewing the tooth laterally (Lee and Eakle, 1984, Rees et al., 2003). They are more common on the buccal and labial aspects of teeth, more common in premolars and molars than canines and increase in number and size with age (Aw et al., 2002, Bernhardt et al., 2006, Wood et al., 2008).

Two studies have attempted to classify NCCLs according to their clinical appearance (Table 1.2) and the type of tooth tissue involved (Table 1.3) (Micahel et al., 2010, Grippo, 1991).

1.3.4.2 Aetiology of NCCLs

The aetiology of NCCLs has been widely accepted as being multi-factorial. Such factors include intrinsic or extrinsic erosion and tooth brushing or dentifrices abrasion. A possible role of occlusal stress from abfraction and bruxism has been suggested (Bergstrom and Eliasson, 1988a, Bergstrom and Eliasson, 1988b, Levitch et al., 1994, Rees, 2006). These factors can interact or operate independently (Bergstrom and Eliasson, 1988b, Braem et al., 1992, Grippo et al., 2004, Bernhardt et al., 2006, Wood et al., 2008, Bartlett and Shah, 2006). In many cases, the predominant main aetiological factor behind the observed NCCL might not be obvious and quite difficult to diagnose (Bartlett and Shah, 2006, Michael et al., 2009, Michael et al., 2010).

1.3.4.2.1 The concept of Abfraction

Abfraction means to ‘break away’ (Braem et al., 1992). The term was first coined in 1991 by Grippo, evolving through the work of Lee and Eakle (1984). Excessive cyclic, non-axial occlusal tooth loading (biomechanical loading) leads to cusp flexure and stress concentration in the cement-enamel junction. The result is tooth structure loss through loss of bond between the hydroxyapatite crystals. This initially leads to crack initiation that progresses and makes the tooth susceptible to further breakdown and bulk enamel loss via erosion and abrasion (Xhonga, 1977, Lee and Eakle, 1984, Grippo, 1991, Braem et al., 1992, Rees, 1998, Palamara et al., 2000, Lee et al., 2002, Grippo et al., 2004, Rees and Hammadeh, 2004, Borcic et al., 2005, Rees, 2006).

Finite Elemental Analysis (FEA) studies have demonstrated that eccentrically loaded premolars demonstrate high stresses in the cervical region (Rees, 1998, Palamara et al., 2000, Lee et al., 2002). This also occurs with maxillary incisors (Rees et al., 2003), teeth in malocclusion (Borcic et al., 2005) and axially loaded teeth (Palamara et al., 2001). These FEA studies have used different force magnitudes in their FEA models and assumed different physical properties of dental tissues. FEA studies are also limited in their ability to simulate the biological dynamics of the oral environment that encompasses not only the teeth but their supporting structures also (Rees and Hammadeh, 2004, Wood et al., 2008, Michael et al., 2009).

The theory of abfraction is based on a limited number of engineering analyses studies consisting of Finite Elemental Analysis (FEA) and photo-elastic models. Very little clinical evidence supports abfraction as the primary aetiological factor behind NCCL or that abfraction even exists (Litonjua et al., 2003, Bartlett and Shah, 2006, Michael et al., 2009, Shah et al., 2009, Wood et al., 2009). Furthermore, a study investigating the association between cervical wear and occlusal wear with periodontal parameters in 30 patients (mean age 59.3±8.9), demonstrated that cervical wear was significantly associated with less plaque accumulation, lack of mobility and the presence of shallow pockets, suggesting that the relatively healthy periodontal status presented in cervial wear patients is due to the role of abrasion as the main aetiology for the noted NCCLs (Pikdoken et al., 2011).

1.3.4.3 Prevalence of NCCLs

The prevalence of NCCL has been reported to vary between 2 and 90% (Shulman and Robinson, 1948, Bergstrom and Lavstedt, 1979, Bergstrom and Eliasson, 1988a, Levitch et al., 1994, Smith and Robb, 1996, Aw et al., 2002, Bardsley et al., 2004, Borcic et al., 2004, Bernhardt et al., 2006). This large variation reflects the relatively few studies reporting the prevalence of cervical tooth wear, the inclusion of different populations, small sample sizes, variations in diagnosis as well as terminology used (Bartlett and Shah, 2006, Wood et al., 2009).

Table 1.2: Classification of NCCLs according to clinical appearance. Adapted from Michael et al., 2010.

Shallow	• Depth ≤ 0.5mm
Concave	• Depth > 0.5mm
Wedge-shaped	• Well-defined internal-line angles • Flat internal floors
Notched NCCL	• Short corono-apical height (0.5 - 1mm) • Long mesio-distal length (4 - 6mm)
Irregular NCCL	• Can't be categorised

Table 1.3: Classification of NCCLs according to tooth tissue involved. Adapted from Grippo, 1991.

Enamel abfractions	• Hairline cracks • Striations • Saucer-shaped • Semi-lunar • Cusp-tip invagination
Dentine abfractions	• Gingival • Circumferential • Multiple • Sub-gingival • Lingual • Interproximal • Alternate • Angular • Crown margin • Restoration margin

1.4 Mental health and tooth wear

Although tooth wear can have detrimental dental effects, yet it can also serve as an important screening and diagnostic criteria for identifying a number of mental and psychological conditions and disorders (Robb and Smith, 1990, Robb and Smith, 1996, Bracha et al., 2005, Hamamoto and Rhodus, 2009, Gungormus and Erciyas, 2009). Mental health is a serious issue, with stress, anxiety and depression accounting for the loss of 56 million working days in the UK due to sickness absences at an estimated cost of £4.1 billion (Confederation of British Industry, 2005). Across Europe, the UK has the highest prevalence rates of common mental disorders amongst general practice attendees, at 18.8% for men and 18.2% for women (King et al., 2008). Furthermore, according to the 2007 Adult Psychiatric Survey of England, covering 13171 households, 15.1% of interviewed adults demonstrated clinically significant neurotic symptoms in the week prior to the interview (Bebbington et al., 2009). Dentists and Dental care professionals (DCPs) have a key role in identifying certain mental conditions and managing/referring them to the appropriate healthcare professional/s. This role can be achieved through the successful diagnosis of the aetiology underlying the observed tooth wear, which in many cases is mentally or psychologically derived.

There are a number of psychological and mental conditions that are manifested dentally in the form of tooth wear. This section will discuss the comorbidity of these conditions and the relevance of other medical conditions and lifestyle factors, such as gastroesophageal reflux disorder (GORD), smoking and diet, in the expression of tooth wear.

1.4.1 Depression

The World Health Organization (WHO) in the International Classification of Diseases (ICD-10) defined depression as a mental disorder characterised by a depressed mood, loss of interest and enjoyment, and reduced energy leading to increased fatigability and diminished activity (World Health Organization, 1992). Other common symptoms of depression include: reduced self-esteem and self-confidence, ideas of guilt and unworthiness, ideas of acts of self-harm or suicide, disturbed sleep and diminished appetite. On the other hand, stress is defined as any threat to the homeostasis of an organism, whether it is physical, psychological, environmental or derived from within the individual (Selye, 1936). Moreover, stress can be a predisposing factor of depression through depletion of serotonin, dopamine and norepinephrine (Anisman and Zacharko, 1982, Caspi et al., 2003).

It is estimated that 9% of British adults suffer from mixed anxiety and depression; making it the most commonly diagnosed mental disorder in the UK (Singleton et al., 2003, Bebbington et al., 2009). Eleven per cent of the Scottish population aged 15 and over use antidepressants on a daily basis (Audit Scotland, 2011). Depression has a high recurrence rate with 50% of depression patients suffering from a second major episode (Kupfer, 1991). Furthermore, 50% of patients initially diagnosed with depression had a persistent diagnosis of the condition one year later (Simon et al., 2002). There is also evidence to support an association between stress, depression and GORD. A study of 4600 participants demonstrated a significantly higher prevalence ($p<0.001$) of anxiety, depression and hostility in participants with GORD symptoms versus those without (Lee et al., 2006). The results of this study agree with those obtained by others (Avidan et al., 2001, Wright et al., 2005, Richard Locke et al., 2004, Martin-Merino et al., 2010). Furthermore, thirty per cent of people with depressive episodes experience lifetime alcohol use problems (Sullivan et al., 2005) and are twice as likely to smoke compared to those without any neurotic disorders (Coulthard et al., 2002).

Tooth wear and depression

Studies have demonstrated an association between depression, stress, anxiety and tooth wear. A cross-sectional survey of 13057 participants in the UK, Germany and Italy reported that participants who suffered from anxiety, stress, smoking, and heavy alcohol drinkers were at a higher risk of reporting sleep bruxism with 8.2% of participants grinding their teeth at least weekly (Ohayon et al., 2001). Another study involving 1784 participants, aged between 30 to 55 years, examined the relationship between reported bruxism and stress experience using questionnaires (Ahlberg et al., 2002). The study demonstrated a significantly positive association between bruxism and severe stress experiences. Psychosocial job stress, low social support from supervisors or colleagues and high depressive symptoms demonstrated a significantly increased risk of bruxism in a study involving 2680 participants (Nakata et al., 2008). These findings tend to agree with those of other studies demonstrating a significant association between tooth wear, depression, stress and emotional stability (Uchida et al., 2008, Gungormus and Erciyas, 2009, Giraki et al., 2010, Strausz et al., 2010, Sutin et al., 2010, Abekura et al., 2011, Fernandes et al., 2012).

There is an evident comorbidity between depression, GORD, alcohol abuse and smoking, with tooth wear being one of the main dental manifestations of such disorders (Table 1).

GORD is often first diagnosed by dentists through observation of tooth wear (Barron et al., 2003, Holbrook et al., 2009). A systematic review of the existing literature was carried out to assess the relationship between GORD and dental erosion (Pace et al., 2008). The review concluded that dental erosion was present in 5 – 47.5% of GORD patients. Research has also demonstrated that nocturnal bruxism can be secondary to acid reflux episodes (Miyawaki et al., 2003, Miyawaki et al., 2004, Machado et al., 2007). There is also some evidence supporting an association between GORD, alcohol intake and smoking (Kaltenbach et al., 2006, Wildner-Christensen et al., 2006). Furthermore, nicotine-intake is significantly associated with bruxism, with bruxers twice as likely to report heavy smoking (Rintakoski et al., 2010a, Ahlberg et al., 2004).

1.4.2 Eating disorders

The two main eating disorders (ED) of importance to dentistry are anorexia nervosa and bulimia nervosa. According to the ICD-10, anorexia nervosa is a disorder characterised by deliberate weight loss, induced and/or sustained by the patient and occurring most commonly in adolescent girls and young women (World Health Organization, 1992). The ICD-10 further states that one of the definitive diagnostic criteria for anorexia nervosa is the presence of a body-image distortion in the form of a specific psychopathology. There maybe associated depressive or obsessional symptoms, as well as features of a personality disorder. On the other hand, bulimia nervosa is a syndrome characterised by repeated bouts of overeating and an excessive preoccupation with the control of body weight, leading the patient to adopt extreme measures to mitigate the ''fattening'' effects of ingested food. Bulimia nervosa shares the same psychopathology, age and sex distribution as anorexia nervosa, but the age of presentation tends to be slightly older (World Health Organization, 1992).

In the UK, anorexia nervosa is reported to affect 1.9% of women and 0.2% of men, and 0.5% and 1% respectively for bulimia nervosa (Wiles et al., 2006). The most common comorbid psychiatric condition in ED is major depression (Herzog et al., 1992, Braun et al., 1994, Bulik et al., 1997). Moreover, the average number of weekly vomits of 371 ED patients was reported to be between 5.13 – 9.17 times per week, with 26.3 – 35.2% of ED patients reporting drug/substance abuse (Krug et al., 2009). High rates of alcohol use disorders, smoking and nicotine dependence are prevalent amongst ED patients (Wiederman and Pryor, 1996, Franko et al., 2005, Anzengruber et al., 2006, Piran and Robinson, 2006, Baker et al., 2010). Furthermore, a study of seventy-eight ED patients and thirty-two healthy controls demonstrated that ED patients consumed on average between 16.3 – 39.5 cans of diet beverages per week compared to 7.4 cans for healthy controls (Klein et al., 2006).

Tooth wear and eating disorders

Dental erosion can be frequently encountered in ED patients. It is estimated that between 35 – 38% of ED patients suffer from tooth erosion (Simmons et al., 1986, Roberts and Li, 1987). A matched case-control study comparing the oral health of fifty-four ED patients and fifty-four healthy participants, matched for gender and age, demonstrated that the prevalence of severe tooth wear was significantly higher (*p=0.005*) in ED patients at 38% compared to 11% of controls (Johansson et al., 2012). Tooth wear is particularly evident on the palatal surfaces of anterior and posterior teeth (Jarvinen et al., 1992, Chadwick and Mitchell, 2001) and is caused by the purging behaviour of gastric acidic contents (Hellstrom, 1977, Hurst et al., 1977) and the elevated consumption of acidic carbonated drinks to boost energy or decrease the reflex hunger stimulus (Moazzez et al., 2000a, Al-Dlaigan et al., 2001b, El Aidi et al., 2011). The association between ED, alcohol consumption, drug use and smoking can further exacerbate tooth wear. The psychological stress, high comorbidity of depression in ED and smoking can trigger bruxism, as previously discussed (Gungormus and Erciyas, 2009). The association between alcohol, drug use and tooth wear will be discussed later in this paper.

The chances of dentists and DCPs coming across ED patients are quite high (Milosevic, 1999), hence they have a crucial role in identifying ED patients and appropriately managing them. On the other hand, a study involving 202 dentists and 367 dental hygienists, demonstrated low scores concerning knowledge of oral and physical cues of anorexia and bulimia amongst study participants (DeBate et al., 2005). More dental hygienists than dentists correctly identified oral manifestations of ED (*p=0.001*). Additionally, female dentists tend to have greater knowledge of oral manifestations of ED compared to male dentists (*p=0.001*) (DeBate et al., 2006). Eighty six per cent of dentists reported that they needed more training in dental management of patients with ED, according to a study involving 258 dentists (Johansson et al., 2009).

1.4.3 Alcohol use disorders

The WHO adopted the term '*alcohol use disorders*' to denote mental, physical and behavioural conditions of clinical relevance associated with the use of alcohol (World Health Organization, 2012). Alcohol use disorders include acute intoxication, harmful use, dependence syndrome, withdrawal syndrome, psychotic disorders and amnesic syndrome. Disorders of special interest are: harmful use and dependence syndrome. Harmful use is defined as a pattern of use that causes damage to health whether physical or mental. On the other hand, dependence syndrome is a cluster of psychological, behavioural and cognitive phenomena in which substance use (such as alcohol or psychoactive drug use) takes a higher priority than other behaviours despite harmful consequences (World Health Organization, 1992).

According to the Prime Minister's Strategy Unit interim analytical report of 2003, it is estimated that in Britain there are 1.8 million people who are very heavy consumers of alcohol, at 50 units for men and 35 units for women per week (Prime Minister's Strategy Unit, 2003b). The report also estimated that 7% of Britain's adult population is alcohol dependent. A quarter of British adults (26%) were assessed as being harmful/hazardous alcohol drinkers (Singleton et al., 2003).

Furthermore, alcohol dependency was associated with neurotic symptoms, major depression and GORD. Neurotic symptoms are present in 30% of those with an alcohol dependency syndrome (Coulthard et al., 2002). The presence of an alcohol use disorder doubled the risk of presence of major depression (Boden and Fergusson, 2011). Likewise, GORD symptoms are present in patients with alcohol dependency (Simmons and Thompson, 1987, Wildner-Christensen et al., 2006).

Tooth wear and alcohol use disorders

Dental erosion is prevalent amongst patients with alcohol dependency and individuals with high wine consumption (Robb and Smith, 1990, Mandel, 2005). A study demonstrated that 49.4% of alcohol dependency patients undergoing rehabilitation suffered from enamel and/or dentine erosion lesions (Manarte et al., 2009a). The tooth wear risk of alcohol use disorders arises, not only from the acidic erosive potential of alcohol, but also from the high comorbidity between alcohol, depression, GORD and smoking, as previously discussed.

Current practices and intentions to provide alcohol-related health advice in primary dental care were examined in a study that involved 175 General Dental Practitioners (GDPs) randomly selected from across Scotland (Shepherd et al., 2011). The results of the study demonstrated that GDPs had relatively poor knowledge on recommended alcohol consumption guidelines and associated risk. Furthermore, GDPs demonstrated a low intention to provide alcohol related advice and exhibited a lack of positive attitude and efficacy towards delivering such advice.

1.4.4 Drug use disorders

The definition of drug use disorders have been previously discussed in reference to harmful use and dependency syndrome definitions, present in the WHO's ICD-10 (World Health Organization, 1992).

In Britain, between 3.7 - 4% of the population is considered to be drug dependent (Singleton et al., 2003, Coulthard et al., 2002). The 2003, Prime Minister's Strategy Unit's Drugs report stated that the UK had over three million drug users (Prime Minister's Strategy Unit, 2003a). The report estimated that, in England and Wales alone, there were over one million amphetamine and ecstasy users in the previous year, with half of them reporting use in the past month. Amphetamines, methamphetamines (MAP) and ecstasy (3,4-methylenedioxymethamphetamine, MDMA) are psychostimulant drugs possessing hallucinogenic and excitatory properties caused by their dopaminergic, serotonergic and adrenergic systemic effects (Cho and Melega, 2001). Moreover, MDMA is frequently used in-combination with cannabis (71%), amphetamine (29%) or cocaine (25%) (Tossmann et al., 2001).

The comorbidity of drug and alcohol abuse, depression and eating disorders is well documented. Psychiatric disorders are present in 45% of drug dependents (Singleton et al., 2003). The use of psychostimulants is significantly higher in eating disorders patients ($p<0.001$) compared to healthy controls, at 17.2 and 6.2% respectively (Krug et al., 2008). MDMA users are at higher risk (53% of users) of developing psychopathological disturbances, with depression reported as the most frequent disturbance (Schifano et al., 1998). Furthermore, a study including 3503 participants reported that 66% of ecstasy users consumed alcohol in combination with MDMA (Tossmann et al., 2001). Another study reported that 93% of MDMA users consumed a mean of three cans of carbonated drinks per 'trip' (Milosevic et al., 1999).

Tooth wear and drug use disorders

A study of three hundred and one MAP dependents demonstrated that 22% of them have been aware of bruxing behaviour and tooth erosion for the past 6 years (Shetty et al., 2010). Furthermore, MAP users who snorted the drug had a significantly higher prevalence of tooth wear ($p=0.005$) in their anterior maxillary teeth, when compared to users who injected, smoked or ingested the drug. MDMA users had a higher prevalence and severity of tooth wear (60%) when compared to non-users (11%), with 93% of MDMA users reporting xerostomia and 89% of them reporting clenching or grinding after taking the drug (Milosevic et al., 1999). The high consumption of carbonated drinks and alcohol (to combat dehydration) and bulimic episodes associated with drug use further compound the present tooth wear through the introduction of an erosive element.

Dental disease may provide a stable and specific medical marker for identifying MAP users, with dentists capable of participating in collaborative care of MAP users through early detection of drug-related oral/dental cues (Shetty et al., 2010).

1.4.5 Mental health, tooth wear and management challenges

Patients with mental health disorders comprise a significant cohort of society that dentists and DCPs will frequently encounter in practice. The management of this patient cohort can be challenging, both medically and dentally. Dentists and DCPs can have an important contribution towards the well being of these patients through early identification of present oral manifestations, appropriate management of the patient and successive oral state monitoring.

Early identification emanates through knowledge and understanding of physical and oral/dental signs, with tooth wear being one of the major ones, of potentially underlying medical conditions. On the other hand, management of patients with mental health disorders can be challenging. Attempting to obtain an accurate patient history, to assist in identifying the underlying aetiology, can be elusive and requires training. Hence, referral to an appropriate healthcare professional (General Medical Practitioner, Clinical Psychologist, Hypnotherapist, Psychiatrist, etc.) might be necessary for a definitive diagnosis and appropriate medical care. Furthermore, dental management can present its own challenges. Assessing and managing tooth wear falls under Primary Care provision as stated by the UK's General Dental Council's learning outcomes for registration, published in May 2011 (General Dental Council, 2011).

On the other hand, patients with mental and psychological conditions can also fall under the provision of Special Care Dentistry according to the Joint Advisory Committee of Special Care Dentistry, as patients who have '*a physical, sensory, intellectual, mental, medical, emotional or social impairment or disability or, more often, a combination of a number of these factors'* (British Society for Disability and Oral Health, 2007).

Further complicating matters, many of these patients present with severe/advanced tooth wear requiring complex treatment plans and potentially a full-mouth rehabilitation approach. With the shortage of present dental literature related to rehabilitation of tooth wear of suitable scientific quality to be included within critical reviews, and the absence of documented outcomes of various tooth wear rehabilitation approaches (Johansson et al., 2008), a definitive treatment plan can be challenging and referral to Secondary/Specialist

Care becomes inevitable. As a result, a clear and definitive dental care pathway for tooth wear patients with mental health disorders seems to be lacking.

Finally, dentists and DCPs can assist in monitoring patients' response and compliance to undergoing medical treatment/therapy through routine monitoring of tooth wear progression. This can be accomplished through the use of dental casts and intraoral clinical examination to identify the rate of progression of tooth wear. Moreover, recent advances in 3D scanning technology can offer an early and accurate means of monitoring tooth wear (Rodriguez et al., 2012a).

1.5 Assessment of tooth wear

In order to quantify the severity and progression of tooth wear, various techniques and indices are available (Johansson et al., 2008). The objective role of a tooth wear index is to classify and record the severity of tooth wear in prevalence and incidence studies (Bartlett et al., 2008). Unfortunately, an objective, accurate and reliable measurement that monitors tooth wear is difficult to achieve (Azzopardi et al., 2001). The available diagnostic indices are either subjective, for example monitoring casts (Bartlett, 2003, Bartlett et al., 2005, Wetselaar et al., 2009) or lack sensitivity in detecting early tooth wear and inadequate in describing the range of wear observed (Donachie and Walls, 1995, Steele and Walls, 2000, Young et al., 2008, Curca and Danila, 2010). Furthermore, relatively newly proposed scoring systems are yet to be tested on a wide scale and lack researcher agreement and consensus (Bartlett et al., 2008, Bartlett, 2010, Mulic et al., 2010, Vailati and Belser, 2010). Thereby, there is not one ideal index that can be used for epidemiological prevalence studies for clinical staging and monitoring of tooth wear (Bardsley, 2008).

These inherent deficiencies in currently available diagnostic tools raise questions in the capability of clinicians towards diagnosing, assessing and possibly treating dental wear. This is further compounded by the multifactorial nature of tooth wear and the variability in its clinical presentation (Meyers, 2008b). Moreover, current assessment regimes do not provide information as to whether the detected tooth wear is pathological, with its incidence and severity increasing with age and requiring restorative intervention, or merely physiological as a result of age and requiring no clinical intervention. This decision-making process is further complicated by the lack of agreement upon acceptable physiological thresholds of tooth wear (Bartlett and Dugmore, 2008, Ganss, 2008, Young et al., 2008, Van't Spijker et al., 2009). This might explain the lack of dental literature related to rehabilitation of tooth wear that may be deemed of suitable scientific quality to be included within critical reviews accompanied by an absence of documented outcomes of various tooth wear rehabilitation approaches (Johansson et al., 2008). On the other hand, recent technological advances in 3D scanning might offer a more objective and reliable method for monitoring the progression of clinical tooth wear and accurately quantifying it.

1.5.1 Tooth wear indices

The objective of a tooth wear index is to classify and record the severity of tooth wear in prevalence and incidence studies (Bardsley, 2008). Currently, a plethora of tooth wear indices exist that have been developed and used in the past 30 years (Eccles, 1979, Smith and Knight, 1984c, Grippo, 1991, Imfeld, 1996a, Lussi, 1996, Bardsley et al., 2004, Hooper et al., 2004b, Fares et al., 2009, Wetselaar et al., 2009, Bartlett, 2010, Vailati and Belser, 2010). These indices are usually numerical, grading or classifying tooth wear based on partial or full-mouth recording, relying on the ability of clinicians to detect the extent of dentine exposure, and varying in their complexity, from the more detailed and narrative indices to the more simple or basic ones.

One of the earliest indices developed was the Eccles index in 1979 (Eccles, 1979). Highly narrative and exceedingly detailed in-nature, the index classified lesions to three classes to be assigned to each of the four visible surfaces of examined teeth (Table 1.4). However, the Eccles index established the foundations for one of the most widely used indices for recording tooth wear, the 1984 Smith and Knight's Tooth wear index (TWI) (Smith and Knight, 1984a) (Table 1.5). The Smith and Knight index, and its modifications (Donachie and Walls, 1995, Al-Majed et al., 2002, Nunn et al., 2003, Dugmore and Rock, 2004a), remains the most Medline-cited index in cross-sectional studies involving adults (Berg-Beckhoff et al., 2008). Recording the presence of tooth wear in full-dentition, regardless of its aetiology, the index was originally designed for epidemiological studies, rather than being tailored for individual treatment needs. However, given the amount of data generated (examination involved all four visible surfaces of all teeth present), the index was time consuming requiring operator training and standardisation with problems arising with inter- and intra-examiner reliability (Young et al., 2008, Lopez Frias et al., 2012). Furthermore, Donachie and Walls challenged the Smith and Knight index-suggested threshold levels for pathological tooth wear and concluded that those thresholds could be misleading when used with older age groups experiencing what might be age-related physiological tooth wear (Donachie and Walls, 1996). Other indices have also been developed to specifically address tooth erosion (Lussi, 1996), relying on extent of dentine involvement and arbitrary quantification of lesions' size to grade the identified erosion (Table 1.6).

Recently, newly developed indices are more simplified, aimed towards screening and recording the identified tooth wear, rather than monitoring and quantifying the progression of the condition. The Basic Erosive Wear Examination (BEWE) (Table 1.7) is based on the Basic Periodontal Examination (BPE) and employs the same protocols (Bartlett et al., 2008, Bartlett, 2010). The index relies on the identification of the tooth with the most severe tooth wear in each quadrant and scoring it, based on the index, from a score of zero (denoting no tooth wear) to a score of three (≥50% hard-tissue loss). The scoring is repeated in all quadrants to give a cumulative score of zero to a maximum of 18. However, the authors do acknowledge that the distinction between the cumulative scores are arbitrary and are not based on research but instead on clinical experience. Similarly, the simplified tooth wear index is a partial-recording index (Table 1.8), although it relies on degree of dentine-exposure as a classification indicator (Margaritis et al., 2011). Another newly developed index that solely addresses anterior maxillary teeth is the ACE classification (Table 1.9) (Vailati and Christoph Belser, 2010). The classification also offers suggestions for various treatment modalities based on the classification of detected tooth wear.

Others have investigated the BEWE and demonstrated that the index was capable of predicting moderate to severe tooth wear, showing a similar distribution of scores to the Smith and Knight index and can be used an effective screening tool (Dixon et al., 2012). However, the study concluded that moderate levels of examiner reliability, unacceptable variation between examiners when assessing extent of dentine exposure, emphasise the importance of examiner calibration and caution when interpreting BEWE scores.

On the other hand, the continuous evolution and development of tooth wear indices presents a number of challenges. All present indices, and the conclusions of studies employing them, are either not comparable (as a result of use of a different or a modified index), have no consensus on use of terminology, or use indicators that are subjective, open to interpretation or poorly reproducible (Ganss et al., 2011). The majority of current tooth wear indices rely on detection of extent of dentine exposure, through colour or morphological changes, as a means for scoring the presence of tooth wear. However, classifying tooth wear based on dentine exposure has been demonstrated to be difficult, poorly reproducible and lacks evidence to support its use as a prognostic tooth wear indicator (Ganss et al., 2006, Holbrook and Ganss, 2008). Many of these indices do no take full-advantage of previously taken study casts as a valuable archived reference of the state of the patients' dentition (Bartlett, 2003). Furthermore, current tooth wear indices have not been calibrated against a so-called gold standard (being a method, procedure or measurement that is widely accepted as being the best available) and lack sufficient supporting studies that favour the use of one index over others (Bardsley, 2008, Berg-Beckhoff et al., 2008). Moreover, the lack of indices capable of accurately quantifying tooth wear has resulted in the absence of clearly defined thresholds differentiating pathological from physiological tooth wear and therefore establishing evidence-based management recommendations (Young et al., 2008) Hence, systematic research in the use of tooth wear indices remains lacking (Ganss, 2008).

A universal tooth wear index needs to fulfil a number requirements. The index should ideally be (Berg-Beckhoff et al., 2008, Young et al., 2008):

- Clinically applicable in general dental practice addressing individual patient-needs
- Adaptable for epidemiological prevalence studies
- Suitable for monitoring progression or arrestment of tooth wear
- Feasible for use in adults and children
- Calibrated and validated against a gold-standard where all quality criteria have been assessed
- Reproducible
- Capable of accurately quantifying distribution of tooth wear
- Capable of indicating treatment needs

Achieving an ideal tooth wear index, attaining all the aforementioned requirements, remains difficult. The solution might lie in the development of two tooth wear indices: a population-based index, and an individual-based clinical index. The former would serve as an initial screening tool, demonstrating incidence and prevalence, while the latter would quantify, monitor and indicate individual treatment needs.

Table 1.4: Eccles index for dental erosion of non-industrial origin (1979).

Class	Surface	Criteria
Class I		Early stages of erosion, absence of developmental ridges, smooth, surfaces of maxillary incisors and canines
Class II	Facial	Dentine involved for less than 1/3 surface; two types. Type 1 (commonest): ovoid-crescent in outline, concave in cross differentiate from wedge shaped abrasion lesions. Type 2: irregular lesion entirely within crown. Punched out.
Class IIIa	Facial	More extensive destruction of dentine, affecting anterior teeth part of the surface, but some are localised and hollowed out.
Class IIIb	Lingual or palatal	Dentine eroded for more than 1/3 of surface area. Gingival white, etched appearance. Incisal edges translucent, flat or hollowed out, often extending into secondary dentine.
Class IIIc	Incisal or occlusal	Surface involved into dentine, appearing flattened or with cupping. Undermined enamel; restorations are raised above surrounding.
Class IIId	All	Severely affected teeth, where both labial and lingual surfaces maybe affected; teeth are shortened

Table 1.5: Smith and Knight tooth wear index (1984). B: buccal; L: lingual; O: occlusal; I: incisal; C: cervical.

Score	Surface	Criteria
0	B/L/O/I	No loss of enamel surface characteristics
	C	No loss of contour
1	B/L/O/I	Loss of enamel characteristics
	C	Minimal loss of contour
2	B/L/O	Loss of enamel exposing dentine for less than 1/3 of surface
	I	Loss of enamel just exposing dentine
	C	Defect less that 1mm deep
3	B/L/O	Loss of enamel exposing dentine for more than 1/3 of surface
	I	Loss of enamel and substantial loss of dentine
	C	Defect less than 1-2mm deep
4	B/L/O	Complete enamel loss - pulp exposure - secondary dentine exposure
	I	Pulp exposure or exposure of secondary dentine
	C	Defect more than 2mm deep - pulp exposure - secondary dentine exposure

Table 1.6: Lussi's index for grading the severity of dentine loss (1996).

Score	Features
Facial surfaces	
0	No erosion, glazed appearance, absence of developmental ridges possible
1	Loss of surface enamel, dentine not involved
2	Erosion into dentine <50% of affected surface
3	Erosion into dentine >50% of affected surface
Other surfaces	
0	No erosion, glazed appearance, absence of developmental ridges possible
1	Slight erosion, rounded cusps, restorations stand proud of enamel, no dentine erosion
2	Severe erosion, more pronounced than score 1, dentine involved

Table 1.7: Basic erosive wear examination (BEWE) (2008).

Score	Features
0	No erosive tooth wear
1	Initial loss of surface texture
2	Distinct defect, hard tissue loss <50% of the surface area
3	Hard tissue loss ≥50% of the surface area

Table 1.8: Simplified tooth wear index (S-TWI) (2011).

Score	Features
0	No wear in dentine
1	Dentine just visible (including cupping) or dentine exposed for less than 1/3 of surface
2	Dentine exposure greater than 1/3 of surface
3	Exposure of pulp or secondary dentine

Table 1.9: ACE classification for anterior maxillary teeth (2010).

Class	Palatal Enamel	Palatal Dentine	Incisal Edge Length	Facial Enamel	Pulp Vitality	Suggested Therapy
Class I	Reduced	Not exposed	Preserved	Preserved	Preserved	No restorative treatment - prevention only
Class II	Lost in contact areas	Minimally exposed	Preserved	Preserved	Preserved	Palatal composites
Class III	Lost	Distinctly exposed	Lost ≤2mm	Preserved	Preserved	Palatal onlays
Class IV	Lost	Extensively exposed	Lost greater than 2mm	Preserved	Preserved	Sandwich approach
Class V	Lost	Extensively exposed	Lost greater than 2mm	Distinctly reduced/ lost	Preserved	Sandwich approach
Class VI	Lost	Extensively exposed	Lost greater than 2mm	Lost	Lost	Sandwich approach

1.5.2 Advances in tooth wear assessment

While clinical tooth wear indices have inherent deficiencies relating to their subjectivity and poor repeatability, recent technological advances in 3D imaging offer the possibility of accurately capturing 3D digitised images of a patient's dentition, whether directly *in-vivo* or *in-vitro* from dental casts. Using commercial image processing software, successive images of a patient's dentition over time may be compared. This provides a visual map of changes and a quantitative measure of tooth surface loss (Persson et al., 1995, Heintze, 2006, Heintze et al., 2006, Persson et al., 2006, Boldt et al., 2009, Higham et al., 2009, Al-Omiri et al., 2010, Bootvong et al., 2010, Palaniappan et al., 2010). The use of such technology provides a quantitative method to measure tooth wear that relies on physical measurements, such as depth of grooves, area of facet or crown height rather than a subjective index (Bardsley, 2008)

Utilising 3D scanning with commercially available imaging software instead of conventional tooth wear assessment requires investigation regarding the accuracy and precision of the resultant scanned image in-relation to the original scanned structures (DeLong et al., 1985, Chadwick et al., 1997, Mehl et al., 1997, Chadwick and Mitchell, 2001, Chadwick et al., 2002, DeLong et al., 2003, Chadwick et al., 2004, Shah et al., 2004, Thomason et al., 2005, Birnbaum and Aaronson, 2008, Zou et al., 2009).

Successful management of tooth wear necessitates appropriate recognition of the condition, stabilisation of the oral environment and when appropriate, intervention and restoration (Meyers, 2008b). 3D scanning technology might offer a more accurate assessment tool for identifying and monitoring the progression rate of patients' tooth wear. This could prove invaluable in management and intervention decisions regarding tooth wear.

Currently, there are two main approaches employed to quantify/detect tooth wear: profilometery (contact/non-contact) and measurements of enamel/dentine thickness. Profilometery relies on scanning the surface of impressions and/or casts taken at different epochs then superimposing, comparing and quantifying the dimensional differences between the scans to detect tooth wear. Lambrechts et al. carried out one of the earliest studies aimed at quantifying tooth wear *in-vivo* using 3D scanning technology

(Lambrechts et al., 1989). The study monitored the progression of tooth wear in twenty-one patients over a period of 4 years using silicone impressions and copper-plated replicas that were examined using a 3D measurement microscope. The study demonstrated that occlusal wear progressed at an annual rate of 29µm for molars and 15µm for premolars. However, Lambrechts et al. relied on a clinically invasive approach of grinding reference points into the enamel of patients in-order to establish reference points for measurement comparisons of subsequent replicas. Other studies relied on the use of markers cemented onto teeth surfaces to act as references during the superimposition of scans to ensure the accuracy of the superimposition and consequently the detected tooth wear (Bartlett et al., 1997, Schlueter et al., 2005). However, when this methodology was employed in a split-mouth clinical study lasting 20 months; 25% of the markers were lost within 3 months, 50% at nine months and 90% of the markers were lost at 20 months (Sundaram et al., 2007). The studies did not involve any independent calibration and assessment of the scanning systems employed. Furthermore, cementing metal markers as references is a methodology that possesses a number of inherent deficiencies: a) the method is an invasive approach that requires active restorative intervention, b) the presence of sufficient interocclusal space is crucial to accommodate the markers and ensure that the markers do not alter patient's present occlusion, c) placement of markers covering the surface of the teeth will have a protective effect on those surfaces and hence alter the baseline of measurements and challenge detected wear measurements.

On the other hand, Chadwick et al. formulated their own scanning system and surface matching software to ensure the accuracy of their tooth wear measurements (Chadwick et al., 1997, Chadwick and Mitchell, 2001, Chadwick et al., 2002, Chadwick et al., 2004). The authors relied on the fabrication of electro-conductive dies that can be scanned using a custom-made 3D probe scanner and custom surface-matching software, with an estimated system precision of 15µm. The developed methodology was rigorously calibrated and assessed, however, the method remains predominantly a research tool that is not commercially available with a number of limitations that will be discussed later.

Al-Omiri et al. used a commercial CAD/CAM Cercon laser system and a tool maker microscope to quantify tooth wear from dental stone dies (Al-Omiri et al., 2010). However, the study did not assess the accuracy and precision of the scanners used nor assessed the dimensional accuracy or dimensional stability of the stone die used, hence, it was not accounted for as part of the scanning system's overall performance.

As for measurements of enamel and dentine, there are two methods that have been employed clinically: Optical Coherence Tomography (OCT) and ultrasound. Wilder-Smith et al, in a randomised, double-blind study used OCT to quantify dental tissue demineralization and enamel loss before and after 3 weeks of acid-suppressive treatment with esomeprazole 20mg or placebo in thirty GERD/GORD patients (Wilder-Smith et al., 2009). However, both methods, OCT and ultrasound, in-addition to other *in-vitro* methods have limitations regarding probe positioning, average thickness of enamel and dentine, time consumption, complexity of methodology, the use of amelo-dentinal junction as a reference and repeatability issues (Huysmans et al., 2011, Schlueter et al., 2011).

Understanding and accounting for the uncertainties and errors of any 3D scanning system, with a clear assessment of all the stages involved-in and leading-to the scanning process, is cardinal when comparing measurements at microns level. One of the important studies addressing this issue was carried-out by Delong et al. in an attempt to assess and calibrate a commercial 3D optical digitising system (Comet 100, Steinbichler Optical Technologies, Neubeuern, Germany) and a custom software (DeLong et al., 2003). The study involved the fabrication of a steel model comprising of seven ball-bearings and a stone-replica of the steel model, both of which were calibrated by a calibration service (QC Inspection Services, Inc., Burnsville, MN, USA) using a coordinate measuring machine (CMM). Impressions were taken of the steel model using disposable impression trays (SmartPractice, Phoenix, AZ, USA), vinyl polysiloxane impression putty (Express STD, 3M ESPE, St. Paul, MN, USA), and an experimental scannable vinyl polysiloxane impression material (Digisil SBR #123948 113; 3M ESPE) in a two-step process, then poured using white improved dental stone (FujiRock; GC Europe, Leuven, Belgium). The study demonstrated that the accuracy of the casts and impressions was 0.024 ±0.002mm and 0.013 ±0.003mm, respectively. However, Delong et al. were not able to directly scan their calibrated steel model due to its reflectivity and the resultant interference with the optical scanning process. Instead they relied on a mathematical model derived from the calibrated model as a 3D reference for comparison with the optical scanner's acquired scans and scanning of the stone model replica. Furthermore, while the authors detail the dimensions of the ball-bearings used in the steel model (diameter 9.522 ±0.001mm), however, the actual dimensions of the model as a whole and its representation to the dental arch remains unclear. Moreover, the time of scan acquirement of the impressions and casts is also unclear, which is critical information given the dimensional changes exhibited by impressions and stone over time.

Tooth wear studies that have employed 3D scanning technology to quantify tooth wear *in-vivo* have reported varying degrees of tooth wear progression. Bartlett et al. reported a tooth wear range of 17.6-108.2µm in thirteen dental erosion patients over a 6-months review period, compared to the seven non-tooth wear healthy controls demonstrating 0.5-15.8µm of tooth wear (Bartlett et al., 1997). Sundaram et al., in their dentine bonding study involving 19 tooth wear patients, demonstrated 100µm of mean tooth wear over a 12-months period (Sundaram et al., 2007). Al-Omiri et al., in their study involving twenty dental students over a period of 6 months, detected tooth wear of 132–193µm using the CAD/CAM laser scanner, however, there was a marked increase in the detected tooth wear at a range of 517–656µm when the tool maker's microscope was used (Al-Omiri et al., 2010). Moreover, Wilder-Smith et al. demonstrated 250µm of wear in thirty GORD/GERD patients over a period of 12 months (Wilder-Smith et al., 2009). The marked differences between tooth wear results from various studies can be due to the differences in populations examined and variations in methodologies employed. However, comparison of these results is made difficult due to the absence of a standardised approach/ protocol for monitoring tooth wear *in-vivo* using 3D scanning technology. There is a lack of an agreed consensus over a 3D scanning system assessment protocol that accounts for and characterises the main elements involved in the 3D scanning process; these main 3D scanning system elements being: the accuracy and precision of the 3D scanner, the accuracy and stability of the replication technique (impression + stone) and the 3D software analysis process. In the absence of such a standardised 3D scanning and analysis protocol, comparison of tooth wear studies' results continue to be challenging and hence hinder the development and the reliability of tooth wear management recommendations.

1.6 Management of tooth wear

There are a number of challenges present when managing tooth wear complicating the treatment planning decision in such complex cases. These challenges are (Mehta et al., 2012c): i) identifying the underlying aetiology of the tooth wear and deriving an accurate diagnosis; ii) uncertainties in knowing the precise stage at which active restorative intervention is needed; iii) lack of understanding of how to restore severely worn dentitions with the aim of attaining a functionally and aesthetically stable restored dentition; iv) a lack of knowledge relating to the availability of contemporary materials and their respective techniques of application.

1.6.1 Principles of management

However, even with the present uncertainties in tooth wear restorative treatment, there seems to be a consensus on the main principles for managing tooth wear cases (Dietschi and Argente, 2011, Kelleher et al., 2012, Mehta et al., 2012c). These main principals emphasis a comprehensive treatment approach that focuses on early intervention through:

1. Comprehensive history taking and identification of present risk factors, resulting in an appropriate differential diagnosis through extensive aetiological clinical/ special investigations, which may include: dietary analysis, intra-oral photographs, study models, sensibility testing, radiographs, referral to other healthcare professionals (Medical practitioner, Clinical psychologist, Nutritionist, etc.), assessment of OVD and RFH, phonetic evaluation and salivary analysis.
2. Understanding and acknowledgement of patient’s wishes, expectations and treatment needs and discussion of various restorative treatment options available.
3. Knowledge of current choices of materials and treatment modalities present for managing tooth wear, from conventional full-mouth rehabilitation approaches to minimally invasive adhesive dentistry alternatives.
4. Appropriate treatment planning and execution, which may include: analysis of study models, diagnostic wax-ups, investigating changes to present Overall Vertical Dimension and smile-line.
5. Maintenance of resultant restorative intervention through raising patient awareness, protective night guard/splint, application of fissure sealants/ adhesive bond on teeth,

regular reviews, repair/replacement of defective restorations and/or addition of new ones.

1.6.2 Conventional versus minimally invasive management

Historically, restorative management of tooth wear involved highly invasive full-mouth rehabilitation approaches comprising of crown-lengthening, multiple crowns, bridges to restore aesthetics, function and form to patients' affected dentition (Lerner, 2008, Malkoc et al., 2009, Song et al., 2010). Conventional management might also involve the delivery of an interim fixed and/or removable prosthesis as a means of assessing altered OVD (Doan and Goldstein, 2007). All-Ceramic crowns, that require extensive removal of sound tooth structure, have also been employed to restore up to 28 teeth (Cortellini and Parvizi, 2003). Others have opted for extremely complex treatment approaches involving crown lengthening surgery, alveolar-bone remodelling, elective endodontic therapy with custom post cores, mini-implants for orthodontic anchorage, in-combination with metal-ceramic crowns and removable partial dentures to manage severe tooth wear (Moslehifard et al., 2012).

While the conventional approach might be the only restorative management-alternative available, especially in severe tooth wear cases, however, a management trend is emerging that utilises less destructive modalities that are minimally invasive and maintain remaining sound tooth tissue and pulp vitality through the employment of adhesive restorative materials (Meyers, 2008a). This restorative management trend is based on biologically sensible aims, which are: the preservation of remaining tooth tissue, a pragmatic improvement in aesthetics and the restoration of patient confidence (Kelleher et al., 2012). The management approach might involve the use of composite restorations (Robinson et al., 2008, Schmidlin et al., 2009, Attin et al., 2012), and composite and gold veneers (Gresnigt et al., 2011, Eliyas and Martin, 2013). Posterior teeth can either be accepted and monitored, or restored using indirect adhesive onlays (metal or composite) (Mehta et al., 2012a, Mehta et al., 2012b) Dietschi and Argente have also proposed specific treatment strategies for each anterior and posterior teeth based on individual tooth status (Table 1.10), and supported the use of composites for build-ups and onlays (Dietschi and Argente, 2011), in agreement with other indices such as Vailati and Christoph Belser, 2010. The paper also proposed a 'biomechanical rule' based on the authors' clinical experience. The rule stated that a strict minimum of 1 mm of material is needed on the restored incisal edge of worn teeth to avoid mechanical failure and the need for frequent repairs. There is limited evidence on long-term survival rates of composite restorations in managing tooth wear cases, however, Hemmings et al. reported a success rate of 89.4% at thirty months in restoring anterior worn teeth (Hemmings et al., 2000). Redman et al., reported a median survival rate of 4 years and 9 months when all failures were considered (Redman et al., 2003), while Poyser et al. demonstrated that only 6% of composite restorations placed on mandibular anterior teeth at an increased OVD ranging between 0.5 – 5mm experienced complete failure over a 2.5 year follow-up (Poyser et al., 2007). On the other hand, Bartlett and Sundaram investigated the use of direct and indirect composite restorations in posterior teeth experiencing severe tooth wear (Bartlett and Sundaram, 2006). The study involved the placement of 32 paired direct or indirect composite restorations in premolars and molars of 16 tooth wear patients and compared them to 28 pairs placed in control patients. Over a 3-year follow-up period, 22% of restorations placed in tooth wear patients fractured and 28% were completely lost compared to an 80% survival rate in controls. The authors concluded that the use of direct and indirect composite to restore worn posterior teeth is contraindicated.

Other clinicians have opted for a mixed approach combining conventional full-coverage crowns on maxillary anterior teeth, composite build-ups and veneers on mandibular anteriors, with adhesive ceramic and gold onlays on posterior teeth (Mizrahi, 2008).

One of the greatest challenges when treatment planning tooth wear cases is the dynamic craniofacial changes in wear patients leading to loss of the Overall Vertical Dimension (OVD), with changes to Resting Face Height (RFH), and resultant dentoalveolar compensation (Berry and Poole, 1976, Zengingul et al., 2007). In cases where a considerable change to the OVD has occurred, clinicians are faced with the choice of conforming to the present OVD or altering it and aiming for a reorganised occlusal approach. The main reasons for altering the OVD are (Lerner, 2008): to gain space for the restoration of worn teeth; to improve aesthetics; or to correct the occlusal relationship. The rationale of increasing OVD to manage severe tooth wear was described and popularised by Dahl through the use of a removable cobalt-chrome anterior bite platform, retained by clasps on the canines and premolars, to raise the occlusal bite plane by 2-3 mm and allow non-contacting teeth to move passively into occlusion (Dahl and Krogstad, 1982). This passive movement occurs through selective supra-eruption of non-contacting teeth concomitant with alveolar growth and intrusion of contacting teeth (Briggs et al., 1997). The altered OVD, with the newly established occlusal plane, is stabilised in 94-100% of patients over a period of 4-9 months(Poyser et al., 2005). The use of a removable appliance retained by clasps complicated patient compliance, hence, the preference of clinicians to use fixed restorations to alter the OVD, whether through the use of conventional crowns and bridges or adhesive, minimally invasive composites, veneers and onlays/inlays.

Disparity in management decisions between clinicians also seems to be geographically dependent. Sabahipour and Bartlett, used a questionnaire to compare tooth wear management preferences between specialist prosthodontists in the United Kingdom and other countries (Sabahipour and Bartlett, 2009). For palatal erosion in maxillary incisors not involving the incisal edges, most specialists chose to cover the worn surfaces using dentine bond and prescribed fluoride mouthwash. On the other hand, where UK prosthodontists preferred to apply direct composites, non-UK prosthodontists were divided, with half of them preferring to leave the teeth untreated, a third choosing to apply composites and 10% choosing to crown the teeth. Another study investigated the general knowledge about diagnosis and treatment of erosive tooth wear in 1262 dentists employed in the Public Dental Health Service in Norway (Mulic et al., 2012). The study demonstrated that only 21% of dentists recorded patients' dietary history, only 27% of them measured salivary secretion, 35% never used study models to document tooth wear status and that fillings were the main choice of treatment in all teeth except lower 2nd molars where fluoride application and/or bonding material application was the treatment of choice.

The lack of consensus in managing tooth wear is not limited to identification of underlying aetiology, monitoring tooth wear progression and choice of restorative intervention but also extends to maintenance of remaining tooth structure and/or restorative intervention. A review study involving 135 papers investigating bruxism management published in the past 40 years, concluded that only 13% of studies were randomised control trials and even these trials do not provide clinicians with strong evidence-based recommendations for the treatment of bruxism (Lobbezoo et al., 2008). The review warned clinicians regarding the 'striking-paucity' of evidence regarding management of bruxism. Other maintenance regimes can offer limited protection to remaining tooth structure, especially against erosion and abrasion, such as fissure sealants (Bartlett et al., 2011a, Wegehaupt et al., 2012), casein phosphopeptide-amporphous calcium phosphate (Ranjitkar et al., 2009) and 1450 ppm fluoride dentifrices and 450 ppm fluoride mouth rinses (Maggio et al., 2010).

At present, the lack of evidence-based consensus on longevity, survival/success rates and complications of various tooth wear management approaches complicate the treatment planning decision in such complex cases and make the preference of one treatment-modality over the other a choice based on limited evidence, case-reports and personal clinician experience/ choice.

Table 1.10: Tooth wear management options based on initial tooth status. Adapted from Dietschi and Argente, 2011.

Area	Tooth Status	Preferred treatment	Alternative treatment
Posterior	No caries lesion Non-restored	Direct composite	Overlay
	Slightly decayed Small to medium-sized restoration(s)	Direct composite	Overlay
	Heavily decayed Large restoration(s)	On-Overlay	Full crown
	Endodontically treated and/or discoloured	Overlay	Full crown
Anterior	No caries lesion Non-restored	Direct composite	Veneer + Direct composite
	Non caries lesion Non-restored Loss of facial anatomy	Veneer + Direct composite	Full crown
	Slightly decayed Small-medium size restoration(s)	Direct composite	Veneer + Direct composite
	Heavily decayed Large restoration(s)	Veneer + Direct composite	Full crown
	Endodontically treated and/or discoloured	Veneer + Direct composite	Full crown

1.7 Statement of problem

The current problem with tooth wear studies is a three tier one: diagnosis, monitoring/quantifying and evidence-based management. The lack of a clear threshold of wear that distinguishes pathological tooth wear from physiological tooth wear complicates differential diagnosis of the condition (Young et al., 2008). The presence of several subjective tooth wear indices that lack standardisation and use varying terminology and challenge the interpretation and comparison of results attained from studies employing those indices (Bardsley, 2008). Furthermore, Lambrechts et al. stated that many of the deviations in the results of tooth wear studies arise from inaccurate replication techniques (impression taking and pouring), repositioning problems (3D software superimposition) and restrictions of the measuring devices (accuracy and precision of scanners) (Lambrechts et al., 1984). Hence, monitoring/ quantification of tooth wear progression and the efficacy of various management modalities employed through the use of an objective, standardised and accurate measuring tool and/or index also remains absent. As a result, there is a shortage of present dental literature related to rehabilitation of tooth wear of suitable scientific quality to be included within critical reviews, and the absence of documented outcomes of various tooth wear rehabilitation approaches (Johansson et al., 2008).

Therefore, there is a clear need for a standardised methodology capable of: objectively quantifying tooth wear *in-vivo*, accurately describing the detected tooth wear, and consequently assisting clinicians in relating it to the underlying aetiology and hence arriving at an accurate diagnosis that would assist clinicians in choosing the appropriate management modality. Furthermore, this methodology needs to be readily available for application by others, with tooth wear progression results feasibly compared across various studies, even when diverse tooth wear populations are being monitored and compared. Finally, the methodology should also be capable of improving clinician-patient communication, in-regards to the condition, and raise patients' understanding and awareness of their tooth wear condition.

1.8 Aims of the study

The primary aim of this study is to develop, calibrate and assess a novel methodology that employs 3D scanning technology in quantifying tooth wear and then assess the applicability and validity of this methodology *in-vivo* through clinical monitoring of the progression of tooth wear in patients over a period of twelve months.

The secondary aim of this study is to provide a descriptive investigation of the patient cohort referred by General Dental Practitioners (GDPs) within Scotland to a secondary care setting (Glasgow Dental Hospital and School) for management of tooth wear and identify outcomes of the patient referral pathway.

2. Methodology

Prior to any attempt to use 3D scanning technology in quantifying and monitoring tooth wear clinically in patients over a period of time, a standardised and calibrated 3D scanning system needs to be formulated that accounts for the four main elements affecting scanning of dental casts over time. These four elements are: the 3D scanner, the impression material, the dental stone and the time of 3D scan acquirement. Henceforth, it was deemed necessary to formulate a multi-stage approach that assesses the effect of all the aforementioned 3D scanning system elements with an aim of determining the overall 3D scanning system's performance.

Once the overall 3D scanning system's performance has been determined, the software 3D analysis stage commences. However, in the absence of an established 3D analysis methodology, that outlines a specific analysis-approach capable of 3D comparison and assessment of scans acquired of patients' dentitions over time, the development of a novel 3D analysis procedure becomes a necessity. Furthermore, such 3D analysis would be under-taken using commercially-available software formulated primarily for industrial applications, rather than dental/medical ones.

The next step, following the calibration of the 3D scanning system and the formulation of a 3D software analysis procedure, is the application of the newly developed 3D scanning methodology *in-vivo* clinically in patients. This stage required successfully attaining ethical approval, followed by the recruitment of suitable participants and then monitoring and quantifying tooth wear experienced by patients' dentition over a period of time, which was twelve months in this study. Finally, once all patient-data has been collect and 3D analysed, this data was used to formulate a novel 3D tooth wear index capable of accurate and reliable quantification and monitoring of tooth wear in patients over time.

This chapter will detail the methodology employed in the current pilot study aimed at quantifying the progression of tooth wear *in-vivo* over a period of twelve months. The chapter comprises of two sections (Figure 2.1): calibration of 3D scanning system and the clinical application of the newly developed methodology.

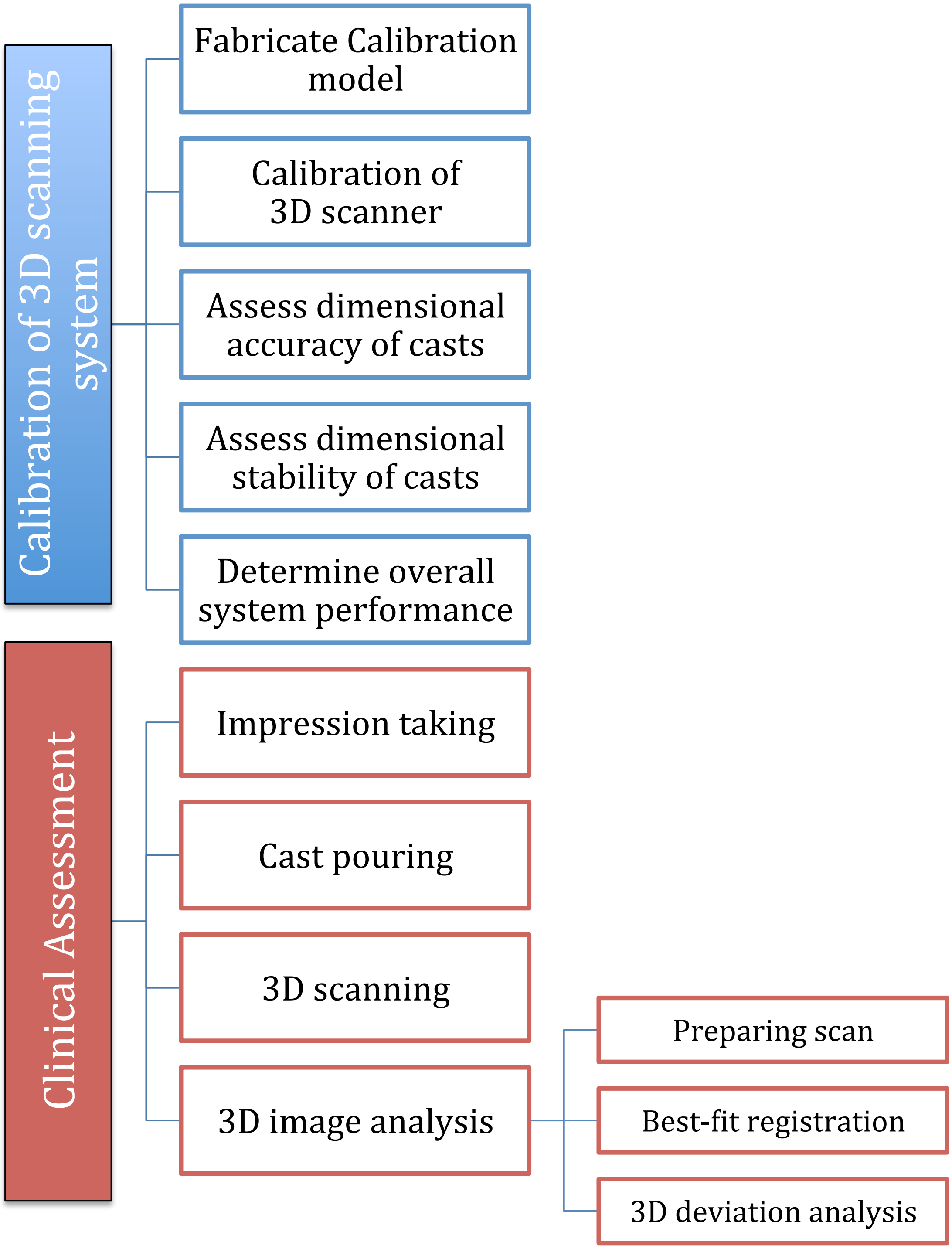


Figure 2.1: Methodological stages for calibrating the 3D scanning system and clinical monitoring of tooth wear in patients.

2.1 Calibration of 3D scanning system

The aim of the calibration of the 3D scanning system stage is to ascertain the scanning system's overall performance. This overall performance is defined, in the study, as the overall accuracy and precision/repeatability of the scanning system, and will establish the threshold at which reliable measurements can be attained from comparison of dental scans acquired at different time-intervals. The overall accuracy and precision of the scanning system is determined through calculating the accuracy and precision of the four main elements of the scanning system: the 3D scanner, the impression material, the dental stone and the time of 3D scan-acquirement, with accuracy being the closeness of a measurement to the actual feature and precision the repeatability of performing a measurement.

2.1.1 Fabrication of a Calibration model

A stainless steel model (SSM) was manufactured by Glasgow University/Clinical Physics Department. The model consisted of seven AISI 440c Grade 100 stainless-steel ball-bearings (10 mm diameter – Atlas Ball & Bearing Co. Ltd, Walsall, U.K) embedded in a horseshoe shaped base at varying depths (Figure 2.2). The dimensions of the SMM were such that it fitted in a standard medium-sized dental impression stock-tray, hence resembling dimensions of the dental arch. The model therefore provided a dimensionally stable and arch-representative sample.

Since high reflectivity targets are notoriously difficult to scan using laser scanners, the surface of the ball-bearings required modifications to achieve a matted, non-reflective surface. Hence, all seven ball-bearings were sand-blasted with Al_2O_3, 60-80μm particles (Saftigrit, Guyson International Limited, North Yorkshire, UK) using a commercial sandblaster (Model: Euroblast 2, 2008, Guyson International Limited, North Yorkshire, UK).

Preceding any comparative measurements made on the SSM, it was deemed necessary to accurately determine the model's dimensions. Currently, contact metrology scanning systems offer the highest accuracy available. Thus, the dimensions of the SSM and the 3D coordinates of the seven ball-bearings were ascertained using a coordinate measuring machine (CMM) with an accuracy of ±(1.7+0.3L/100)µm, where L is the length of the artefact, with the CMM calibrated in-accordance with ISO 10360-2 (2009) (2009)(MitutoyoCrysta Apex-C CMM 544, PH10 head & TP20 standard-force module, software: Mitutoyo MCOSMOS-2 v.2.4.R9 edition 11, Mitutoyo, Kanagawa, Japan). To ensure accuracy, measurements were conducted by a commercial metrology laboratory (Renishaw, Wotton-under-Edge, Gloucestershire, UK). At this stage, the X, Y and Z coordinates of the SSM sphere centres were determined. This was achieved through the use of thirteen points taken by the CMM of the surface of each sphere. These points were then analysed using the Geometric Modelling Library (GML) software (http://www.renishaw.com/geometricmodelling/ en/the-gml--14749) to find the centre of each sphere. Relative length measurements were carried-out from one sphere centre to another using measurement vectors. Seven spheres produce 49 possible vectors, however, we only need to ensure that we cover the volume of the SSM. Hence, nine vectors were selected between sphere centres ensuring model volume coverage. Thereafter, the lengths of the nine vectors between the sphere centres were calculated and the X, Y and Z coordinates of each sphere determined (Figure 2.2 and 2.3). The same procedure was repeated three times, for each SSM ball-bearing and results recorded.

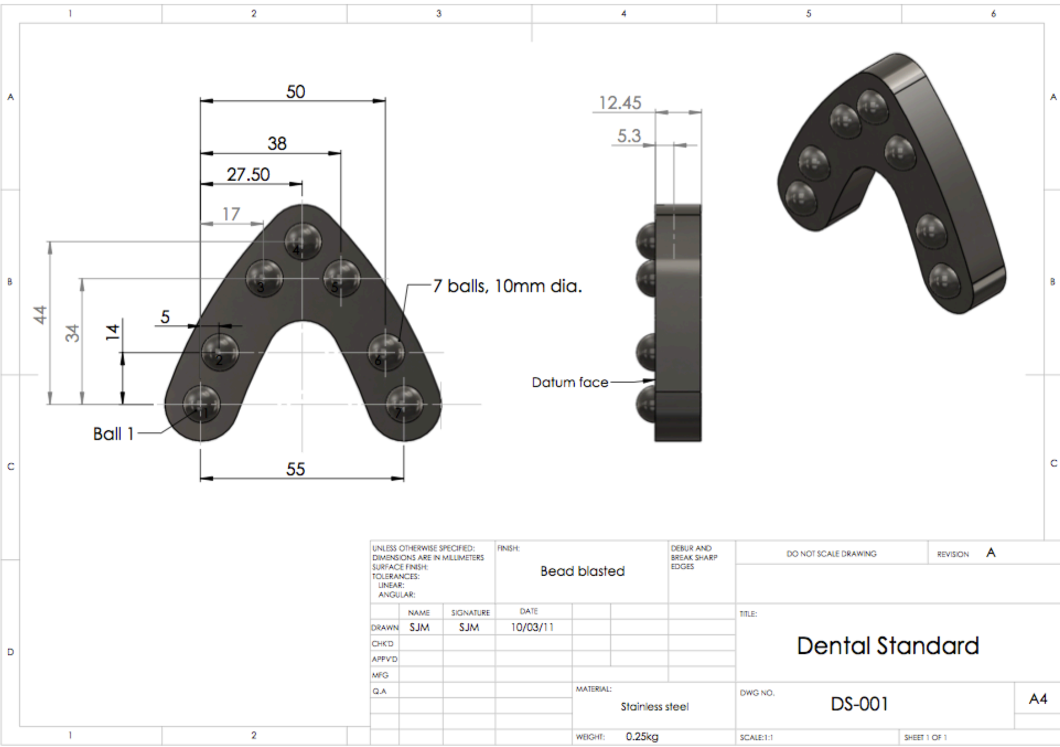


Figure 2.2: Stainless steel model (SSM) specifications. Dimensions in millimetres.

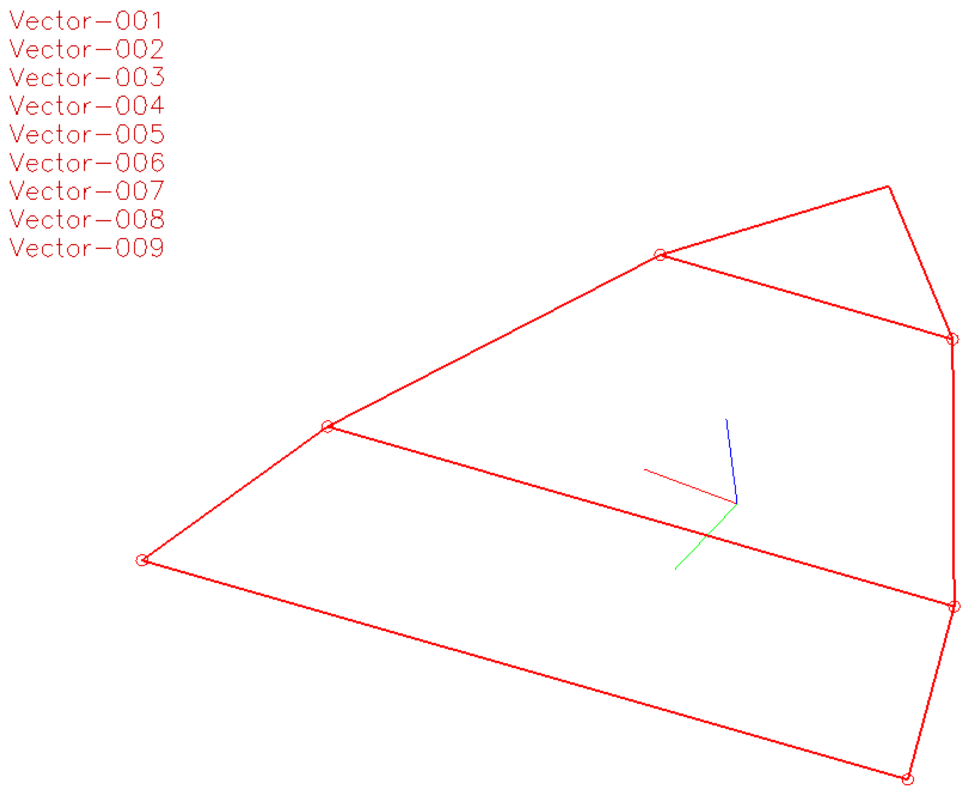


Figure 2.3: Nine vectors measured between centres of the 7 Stainless Steel Model (SSM) spheres using the Coordinate Measuring Machine (CMM). These vectors were used to determine the X, Y and Z coordinates of the 7 SSM spheres.

2.1.2 Calibration of contact and non-contact 3D scanners

The aim of this stage is to identify the accuracy and precision of two 3D scanners. A contact stylus-profilometer dental CAD/CAM scanner (*incise*™, Renishaw, Wotton-under-Edge, Gloucestershire, UK) and a non-contact class-II laser arm-scanner (FARO™ laser scan-arm V3, FARO, Florida, USA).

The *incise*™ contact scanner (Figure 2.4) relies on a stylus-profilometer (1mm diameter ball-end probe, probing force of 0.5N/mm), high-resolution optical scale for an accurate position feedback, and a high-speed controller, with sub-micron resolution for both probe and encoder. The *incise*™ calibration involves the use of two ball-end styli (1 and 3mm diameter) to contact-scan a manufacturer's pre-calibrated-ball, in-accordance with ISO10360-part 4 (1994).

The FARO™ scanning arm (Figure 2.5) relies on a 640 points/line 660nm, CDRH Class II/IEC Class 2M laser for scanning with a scan rate of 30 frames/second. The FARO™ calibration involves probe and high-density laser scanning of a manufacturer-supplied metal block with a non-reflective surface.

Prior to scanning, both scanners were calibrated according to manufacturers recommendations. Thereafter, the now calibrated SSM was scanned three times (each scan represents 7 spheres, $n= 21$) using each of the scanners, incise™ and FARO™ scanners, and stereolithography (STL) images were produced. For the *incise*™, the 1mm diameter ball-end stylus was used for scanning. The STL images once generated were exported to a surface matching software (Verisurf™ X5) in the form of a point cloud. Areas on the surface of the scanned spheres (square patches) were manually selected to include at least twenty thousand surface data points and a Computerised Automated Design (CAD) 3D sphere was generated to fit the selected patch area on each of the scanned calibrated model's seven spheres (Figure 2.6 and 2.7). The use of surface data points acquired from the sphere's surface, to determine each sphere centre and diameter, eliminates the need for a reference marker when 3D superimposing and comparing consecutive scans of the SSM model. A report was then generated indicating the X, Y and Z coordinates, and the radius of each of the CAD generated spheres. The same method was repeated for all calibrated model STL images (Table 2.1).

The coordinates of seven sphere centres calculated from surface data of laser scanning and dental stylus profilometer were compared with that of seven sphere centres measured by the CMM (Mitutoyo™ Crysta Apex-C CMM 544). At first, the seven sphere centres of individual scanning ($\mathbf{X}_i^{scanning}$, $i=1 \ldots 7$) were rigid aligned to the seven sphere centres of the CMM ($\mathbf{X}_i^{cmm}$, $i=1 \ldots 7$) by minimizing a square error criterion given by

$$sqm = \sum_{i=1}^{7} \| \mathbf{X}_i^{cmm} - \mathbf{R}\mathbf{X}_i^{scanning} - \mathbf{T} \|$$

Where $\mathbf{R}$ is the rotation and $\mathbf{T}$ the translation between the configuration of these centres. Rotation is the motion of a rigid body around a fixed point and translation is a function that moves every point a constant distance in a specified direction (Kindle, 1950). Since the independent scans of the calibration model have no common co-ordinate frame of reference, it was first necessary to align the co-ordinate frames using a geometric transformation. The distances between the corresponding sphere centres of the *incise*™ and FARO™ scans and the CMM were calculated using MATLAB™ (R2012a) in order to find the mean errors and standard deviations of the scanner, hence establishing the relative performance of the scanner.

For each scanning technique, the seven spheres' centres established a rigid basis for each measurement. These centres are fixed –relative to each other- for each individual CAD model. The objective of the transformation being to minimise the $\|Er\|^2$fn of the seven centres as a whole under the geometric transformation.

The scanning data were rigid aligned to the CMM centres; the distances between the corresponding sphere centres of the scanning and the CMM were calculated in order to find the mean errors and standard deviations of the scanners. Once a common co-ordinate frame of reference was established, the differences between the CMM model and the scanned models were calculated, hence establishing the mean and relative performance of the scanners.

Figure 2.4: *incise*™ contact stylus profilometer. (Renishaw, Wotton-under-Edge, Gloucestershire, UK)

Figure 2.5: FARO™ laser scanning arm (FARO, Florida, USA).

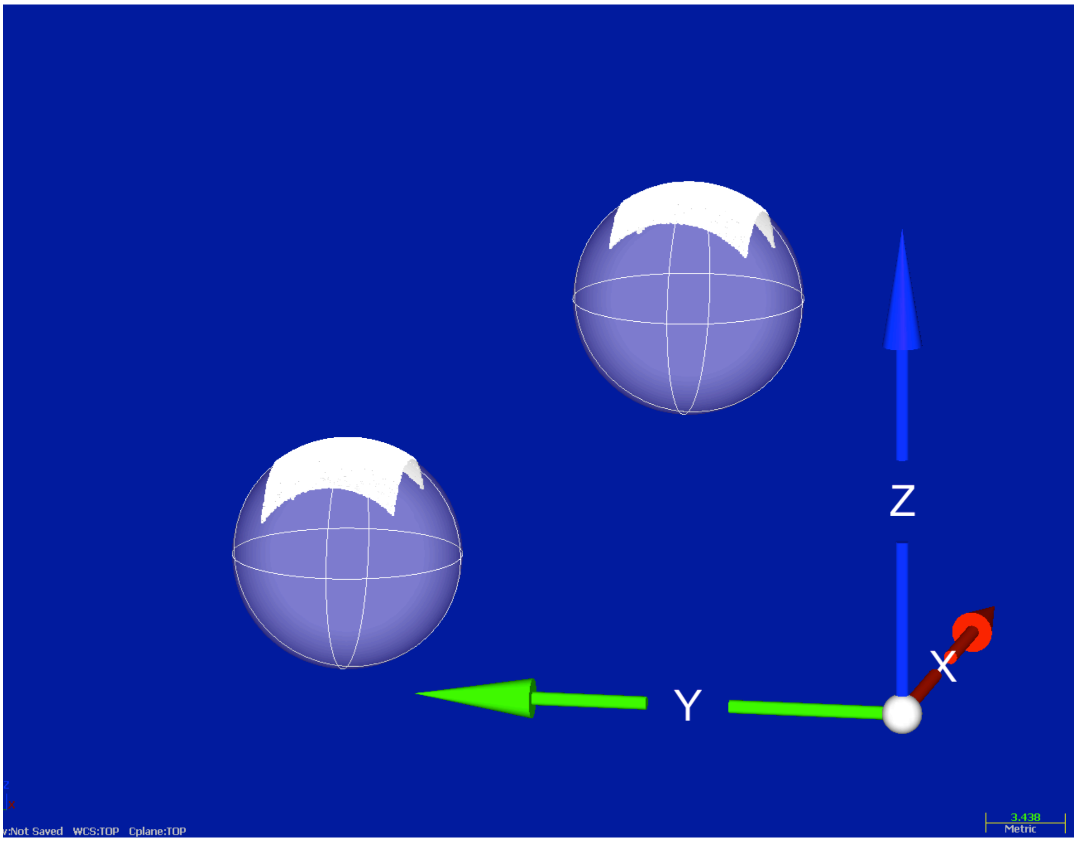


Figure 2.6: Selection of patch area on surface of individual SSM spheres' scan and fitting of Computerised Automated Design (CAD) generated spheres onto selected scan patches using Verisurf ™ software.

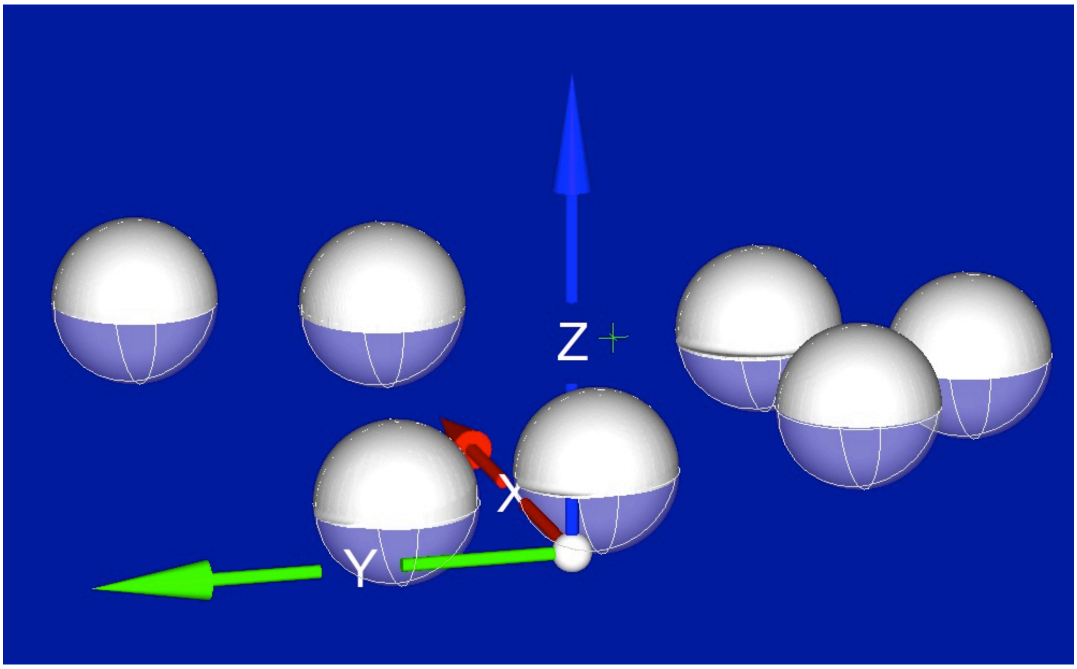


Figure 2.7: CAD spheres (transparent) fitted to SSM's *incise*™ scanned spheres (solid) using Verisurf ™ software. Process repeated for each of the 3 scans of the SSM with each scan representing 7 spheres, *n*= 21. Diameter and X, Y, Z coordinates of CAD fitted spheres were then used to identify the accuracy and precision of the scanner.

Table 2.1: Example of Verisurf™ inspection report demonstrating the X, Y and Z coordinates of *incise*™ scanned spheres.

C:\Users\faro\Documents\my mcamx5\DATA\Reports\T.pdf

Verisurf Inspection Report

Date: 10/27/11
Time: 19:05:29
Serial Number:
Part Name:
Work Center:
Shift:
Dwg #:
Part ID:
Work Order #:
Inspector:

VERISURF. The difference is measurable

Measurements

Sphere1 WCS: FEATURE WCS 2	Measured	Nominal	+Tol	-Tol	Dev
X	0.0000	0.0000	0.0100	-0.0100	0.0000
Y	0.0000	0.0000	0.0100	-0.0100	0.0000
Z	0.0040	0.0040	0.0100	-0.0100	0.0000
Radius	5.0003	5.0003	0.0100	-0.0100	0.0000
Diameter	10.0005	10.0005	0.0100	-0.0100	0.0000
Sphericity	0.0149		0.0100		0.0149

Sphere2 WCS: FEATURE WCS 2	Measured	Nominal	+Tol	-Tol	Dev
X	5.0110	5.0020	0.0100	-0.0100	0.0090
Y	14.0070	14.0070	0.0100	-0.0100	0.0000
Z	-0.0039	0.0020	0.0100	-0.0100	-0.0059
Radius	4.9951	4.9951	0.0100	-0.0100	0.0000
Diameter	9.9901	9.9901	0.0100	-0.0100	0.0000
Sphericity	0.0127		0.0100		0.0127

Sphere3 WCS: FEATURE WCS 2	Measured	Nominal	+Tol	-Tol	Dev
X	17.0227	17.0060	0.0100	-0.0100	0.0167
Y	33.9917	33.9970	0.0100	-0.0100	-0.0053
Z	0.1986	0.0540	0.0100	-0.0100	0.1446
Radius	5.0008	5.0008	0.0100	-0.0100	0.0000
Diameter	10.0016	10.0016	0.0100	-0.0100	0.0000
Sphericity	0.0112		0.0100		0.0112

Sphere4 WCS: FEATURE WCS 2	Measured	Nominal	+Tol	-Tol	Dev
X	27.5060	27.2490	0.0100	-0.0100	0.2570
Y	43.9862	43.9940	0.0100	-0.0100	-0.0078
Z	0.6141	0.1640	0.0100	-0.0100	0.4501
Radius	5.0047	5.0047	0.0100	-0.0100	0.0000
Diameter	10.0094	10.0094	0.0100	-0.0100	0.0000
Sphericity	0.0131		0.0100		0.0131

Sphere5 WCS: FEATURE WCS 2	Measured	Nominal	+Tol	-Tol	Dev
X	37.9867	37.9970	0.0100	-0.0100	-0.0103
Y	33.9829	33.9940	0.0100	-0.0100	-0.0111

Page: 1 of 2

2.1.3 Assessment of dimensional accuracy of dental casts

The aim of this stage is to identify the initial dimensional accuracy of dental stone casts fabricated from three different types of impression materials: alginates, polyethers and polyvinylsiloxanses. To do so, impressions were taken of the CMM calibrated SSM. To ensure accurate impression making, custom-trays were fabricated using light-cured acrylic resin (Invido Lux™ - VOCO GmbH, Cuxhaven, Germany) with a 4 mm spacer and light-cured for 5 minutes then left for 24 hours at room temperature to ensure complete polymerisation.

Three types of materials were used for impression making: alginate (Exact™, fast set – UnoDent, Essex, U.K), polyether (Impregum™ Penta Soft – 3M™ ESPE™, MN, U.S.A) and polyvinylsiloxane (Extrude™, type 2 medium consistency – Kerr, MI., U.S.A). For each of the three impression materials, three impression-takes were acquired of the SSM's seven ball-bearings using the fabricated special-trays (Figure 2.6). The impression materials were mixed according to manufacturer's recommendations. Once taken, the impressions were visually inspected for voids, air-bubbles and discrepancies. If deemed satisfactory, the impressions were disinfected for 10 minutes (Perform®-ID, 3%, Schülke&Mayr GmbH, Norderstedt, Germany) then poured within 24 hours of taking, otherwise retaken. Suprastone die stone (ISO Type IV dental stone, KerrLab, CA., U.S.A) was used for the pouring of the impressions. The die stone was mixed according to manufacturer's recommendations and using vacuum mixing (EasyMix Vacuum Mixer, Bego™, Bremen, Germany) and vibration (Denstar-500, Denstar, Daegu, Korea) to minimise casting errors. Impressions were left for one hour prior to retrieval of the stone casts. All impressions were taken and poured by the first author. Three stone casts, comprising the 7 SSM ball-bearings/spheres, were fabricated for each type of impression material. All casts were then stored dry at room temperature (24˚C).

In-order to establish the dimensional accuracy of casts produced from Alginate (Alg), polyether (PE) and polyvinylsiloxane (PVS) impression materials, the resultant SSM stone cast replicas were scanned at 24 hours post-pouring using the *incise*™ scanner and STL scan images generated (Figure 2.7). Scanning at an earlier stage was avoided to allow satisfactory setting of the die-stone and hence minimising any potential damage resulting from the stylus contact-scanning against soft and potentially incompletely set stone (Ireland et al., 2008).

Each impression material had three SSM stone replicas fabricated, on which 5 spheres were selected. The spheres were then contact scanned, giving a total sample size of 15 spheres per impression material type.

Scanned images of the 15 spheres were again processed using the Verisurf software for each type of impression material poured cast and the diameter and 3D-coordinates of the 15 stone sphere centres determined. Thereafter, the mean-diameter of the stone spheres, acquired at 24 hours post-pouring (S^{24}), for each impression material, were compared to those of the original SSM spheres (S^{O}) attained through the CMM. The difference in mean diameter measurements and standard errors between S^{O} and S^{24} were calculated to demonstrate the dimensional accuracy of the casts poured from the three types of impression materials.

Figure 2.6: Impression taking procedure of Stainless Steel Model using special trays.

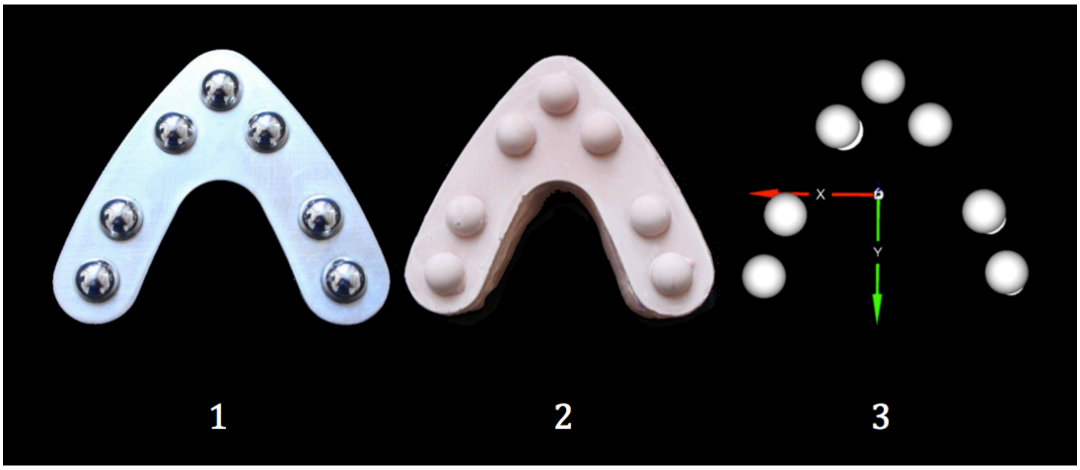


Figure 2.7: Multi-stage approach for 3D-assessment of dimensional accuracy and dimensional stability of impression poured stone casts. Coordinate Measuring Machine calibrated Stainless Steel Model (SSM) (1), Stone cast replica of SSM (2), and 3D scan of stone cast replica (3).

2.1.4 Assessment of dimensional stability of dental casts over time

Monitoring of stone casts' dimensional stability over time was achieved through scanning the previously fabricated SSM stone spheres and measuring their diameter at different time intervals of 48 hours (S^{48}), one week (S^{WK}) and one month (S^{M}). The resultant scans were then compared to the respective 24 hours scan (S^{24}), which served as a reference baseline. The mean-diameter differences between the sphere scans (S^{24} and each of S^{48}, S^{WK} and S^{M}) were measured and dimensional stability determined.

The sample size scanned at each time interval was 27 spheres. This sample size comprised three spheres per impression-take (3-takes in total) for each of the three impression material types. For clarity, all samples were poured using the same dental stone product batch, stored under the same conditions, scanned at the same time intervals and then compared to their respective S^{24} scans. Therefore, it is assumed that all stone casts exhibited similar dimensional changes over the measurement period. Hence, the decision to amalgamate the samples, poured from the three types of impression materials, seemed reasonable.

2.1.5 Determination of the overall 3D scanning system performance

Assessing the uncertainty/ error of each stage is essential to ensure the 3D tooth wear measurements made are robust and appropriately detailed for others to verify/contest.
Each stage – calibration of the 3D scanner, model production (impression taking and stone cast fabrication) and cast storage – has an uncertainty/ error associated with it (Figure 2.8). The uncertainty/ error refers to the scatter of values obtained by repeated measurements taken of an artefact when attempting to identify the true measurement value of that artefact (Kirkup, 2012). This scatter of value, referred to as the coverage interval, enables us to determine an interval within which the true value of the measurement of the artefact lies. According to the Guide to the expression of Uncertainty in Measurement (GUM, United Kingdom Accreditation Service: M3003. The expression of uncertainty and confidence in measurement, edition 3, Nov 2012; Appendix D), overall uncertainty for independent stages of a measurement system is calculated using the **principle of propagation of errors**.

The standard deviation is routinely used to express the uncertainty of any measurement stage. For this study, the standard deviations for each stage are:

- Calibration of the 3D scanner, $\partial_{\text{calibration}}$ (∂_1)
- Dentition replication (impression taking + stone cast fabrication), $\partial_{\text{replication}}$ (∂_2)
- Cast dimensional stability during storage, $\partial_{\text{storage}}$ (∂_3)

Therefore, applying the **principle of propagation of errors** to determine the overall 3D scanning system uncertainty/error (α_{system}) gives this expression:

$$\textbf{Overall Standard Deviation} = \sqrt{\partial_1^2 + \partial_2^2 + \partial_3^2}$$

However, this assumes that the sample size is the same in each of the measurement stages. This was not the case here. To accommodate this, the standard error, $\mathbf{St_{err}}$ must be employed.

The standard error is defined as:

$$\mathbf{St_{err}} = \frac{\boldsymbol{\partial}}{\sqrt{\boldsymbol{n}}}$$

∂ = Standard deviation

$\boldsymbol{n}$ = Sample size used

Hence, the overall scanning system standard error **(Overall $\mathbf{St_{err}}$)** is calculated as:

$$\textbf{Overall } \mathbf{St_{err}} = \sqrt{\left(\frac{\boldsymbol{\partial_1}}{\sqrt{\boldsymbol{n1}}}\right)^2 + \left(\frac{\boldsymbol{\partial_2}}{\sqrt{\boldsymbol{n2}}}\right)^2 + \left(\frac{\boldsymbol{\partial_3}}{\sqrt{\boldsymbol{n3}}}\right)^2}$$

Once the overall 3D scanning system error (**Overall $\mathbf{St_{err}}$**) was calculated, the overall 3D system coverage interval/ 95% confidence interval (95% C.I) was determined through (Hackshaw, 2009):

$$\textbf{95\% C.I} = \pm \textbf{ 1.96 x Overall } \mathbf{St_{err}}$$

The calculated overall 3D system coverage interval represents the overall scanning system performance ($\boldsymbol{\alpha}_{\textbf{system}}$) which identifies the accuracy range at which reliable measurements can be acquired from 3D scanning stone casts, poured at different intervals of time, using different material types of impressions taken of patients' dentition.

However, the calculated overall 3D scanning system performance relates to measurements taken from a single cast scan, with a single set of uncertainties/ errors. When comparing and 3D deviation analysing two scans taken of two subsequently acquired casts, each scan with its own set of uncertainties/ errors, both sets of uncertainties/ errors need to be summed and hence giving rise to the relative 3D scanning system performance (Taylor, 1997), where:

$$\boldsymbol{\alpha}_{\textbf{relative}} = \boldsymbol{\alpha}_{\textbf{system}} \textbf{ x 2}$$

$\alpha_{relative}$: Relative 3D scanning system performance

α_{system}: Overall 3D scanning system performance for scanning one cast

Figure 2.8: The over all scanning system performance has been identified through the assessment of the accuracy and precision of the 3D scanner, assessment of the dimensional accuracy of impression fabricated dental casts and assessment of the dimensional stability of the dental cast at the time of scan acquirement.

2.1.6 Software analysis

Clinically, in order to monitor tooth wear progression over time, a cast replicating the patient's dentition was fabricated and scanned initially, with the resultant point cloud scan then considered as a reference scan (T^O). At a later date, another study cast of the patient was acquired, scanned and the resultant scan considered as the experimental scan (T^1), which was then compared to T^O using 3D matching software to detect any dimensional changes to the dentition. The software used in this study was Geomagic Qualify™ (Geomagic, V.2012, N.C, U.S.A). The T^O and T^1scan data point-clouds were exported to Geomagic Qualify™ for best-fit registration/alignment and deviation/comparison analysis.

In this study, the *incise*™ scanner was used to scan patients' dental casts. Once scanning was complete, the image had to be exported to Renishaw's GML software as an RBF (Retrospect Backup File), where it was then converted into an ASCII (American Standard Code for Information Interexchange) (Figure 2.9). The ASCII file could then be read by Geomagic Qualify™ and converted to an STL file for 3D analysis.

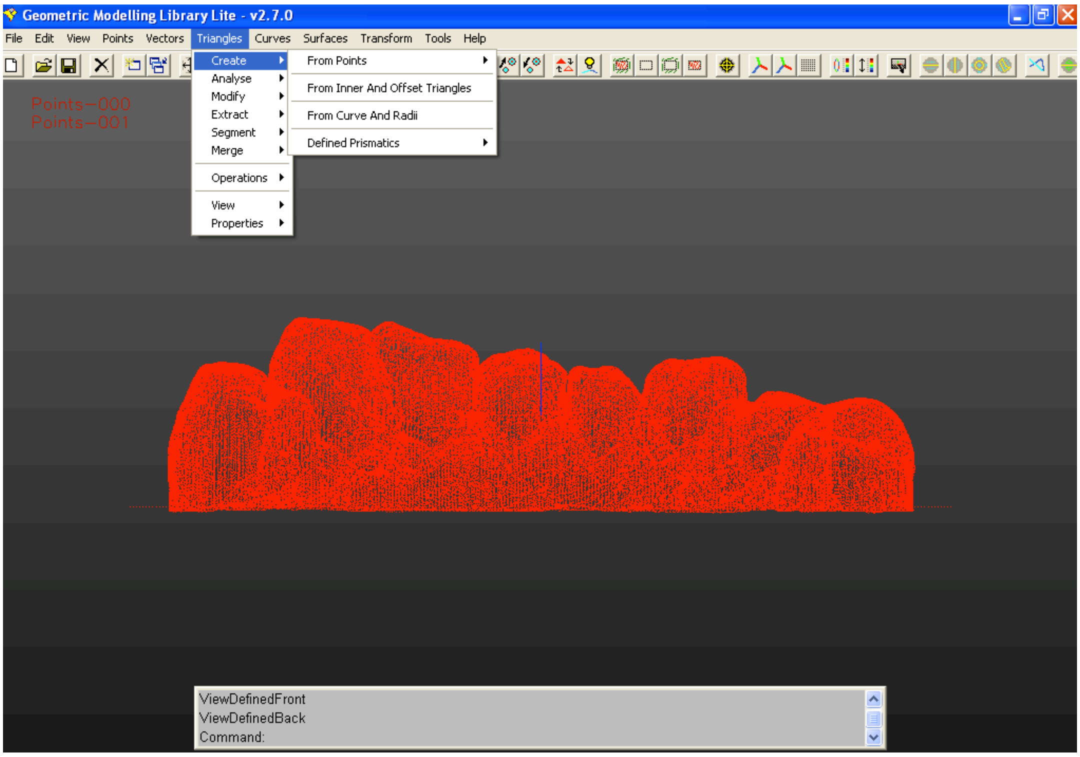


Figure 2.9: Geomagic Modelling Library was used to convert the *incise*™ exported RBF (Retrospect Backup File) to ASCII (American Standard Code for Information Interexchange) that can then be used by Geomagic Qualify™.

2.1.6.1 Preparing scan for analysis

Prior to initiating scan analysis, the STL scan images need to be prepared for the procedure. The preparation stage involved visual identification and elimination of any obvious errors, discrepancies or voids present on the scans, which might have occurred during the scanning procedure or ensued during impression taking and/or casting stages and were not identified at an earlier stage. This is necessary to ensure true superimposition of scans, during Best-fit registration, and the subsequent scans-comparison during deviation analysis. Hence, appropriate preparation/trimming of scan will reduce the potential of error misalignment of scans due to the presence of anomalies on the surface of one or both scans, T^O and T^1. Once these obvious discrepancies have been identified, they were selected and cropped using the lasso tool present in Geomagic Qualify™. Moreover, the soft tissue area surrounding the scanned teeth was also selected and cropped out. Soft tissue changes developing over time, between initial scan and later scans, might potentially interfere with Best-fit registration of scans and give rise to false deviation analysis results.

2.1.6.2 Best-fit Registration

The aim of the best-fit registration was to transform multiple 3D datasets into the same coordinate system so as to align overlapping components of these sets (Tam, 2013). Best-fit registration is achieved through the software's complex algorithm that randomly selects a number of points in the T^1 scan then attempts to identify identical points on the reference T^O scan and uses them as a reference to superimpose T^1 onto T^O (Figure 2.10).

Best-fit registration was undertaken on an individual tooth basis, whereby the same tooth was selected on T^O and T^1 scans and then registered independently from the remaining teeth. For software registration purposes, T^O point cloud was converted to a polygon for it to be selected as a reference-scan. Once selected and cropped, the respective tooth present in T^O and T^1 scans underwent an initial best-fit registration, where the T^1 scan was superimposed onto the reference T^O scan using a randomly selected 300-point sample (Figure 2.9), followed by a more exhaustive 1500-point sample registration. To ensure repeatability of the Best-fit registration, the exhaustive 1500-point sample registration was repeated three times. This process was then repeated for each of the scanned teeth.

Once the best-fit registration between T^O and T^1 is complete for each individual tooth, the data file is saved as an STL. Thereafter, all six individually best-fit teeth present in each arch (upper/ lower) are imported and merged to form a complete arch (Figure 2.10). Merging the STL files, rather than combining them, preserves the individual best-fit registration during 3D deviation analysis.

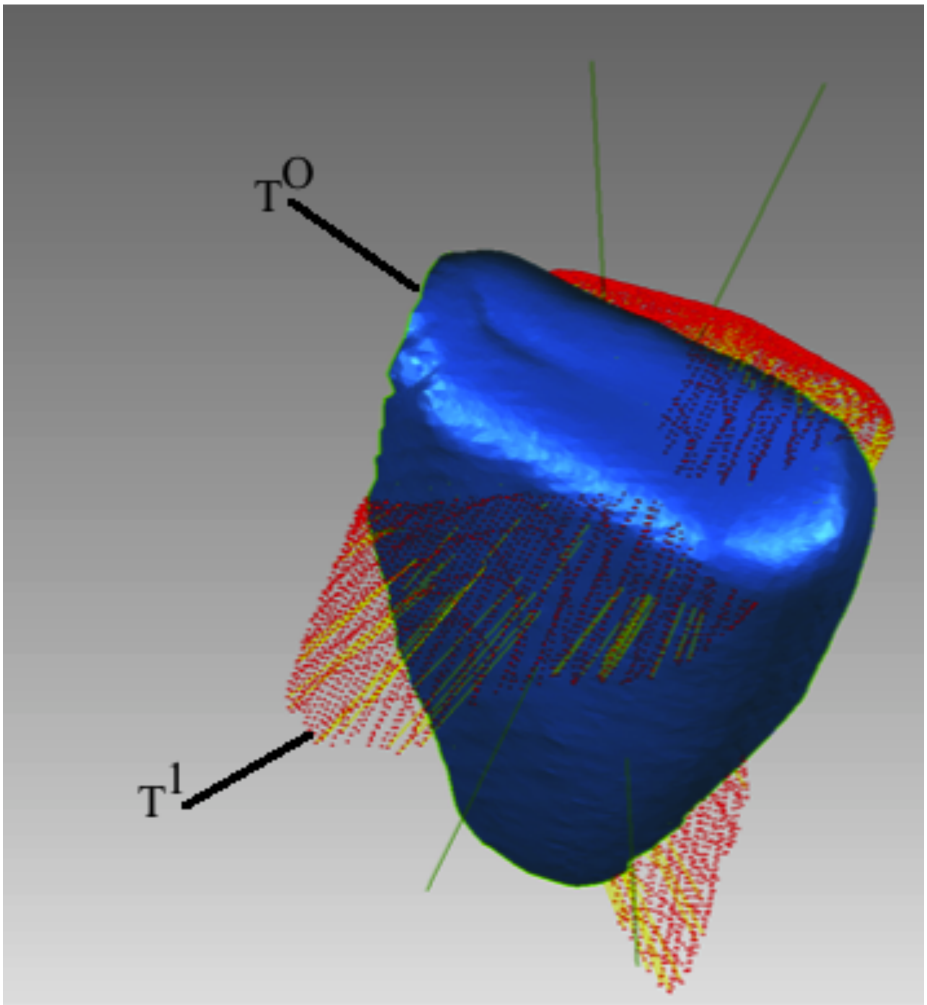


Figure 2.10: Best-fit registration process of experimental T^1 point cloud scan of a single tooth onto the respective reference polygon scan T^O using Geomagic Qualify™ 3D matching software. T^1 represents a scan of patient's dentition acquired 12-months post T^O scan.

2.1.6.3 3D Deviation Analysis

The aim of the 3D deviation analysis was to calculate the square mean distance difference between points present in the experimental scan T^1 and those of the reference scan T^O in the X, Y and Z coordinates.

3D deviation analysis produced a colour-coded surface mapping of the dental scan indicating the positive and negative dimensional differences between the teeth present in T^1 and T^O datasets. A positive value dimensional difference would indicate that T^1 was dimensionally larger than T^O, denoted by the yellow-red spectrum on the colour coded surface map. No dimensional difference, zero value, would be denoted as green on the color-coded surface map. While a negative value dimensional difference would indicate that T^1 is dimensionally smaller than T^O, denoted by the turquoise – blue spectrum on the colour-coded surface map. Finally, a statistical analysis report was generated and exported detailing the depth and distribution of these dimensional differences in the X, Y and Z coordinates.

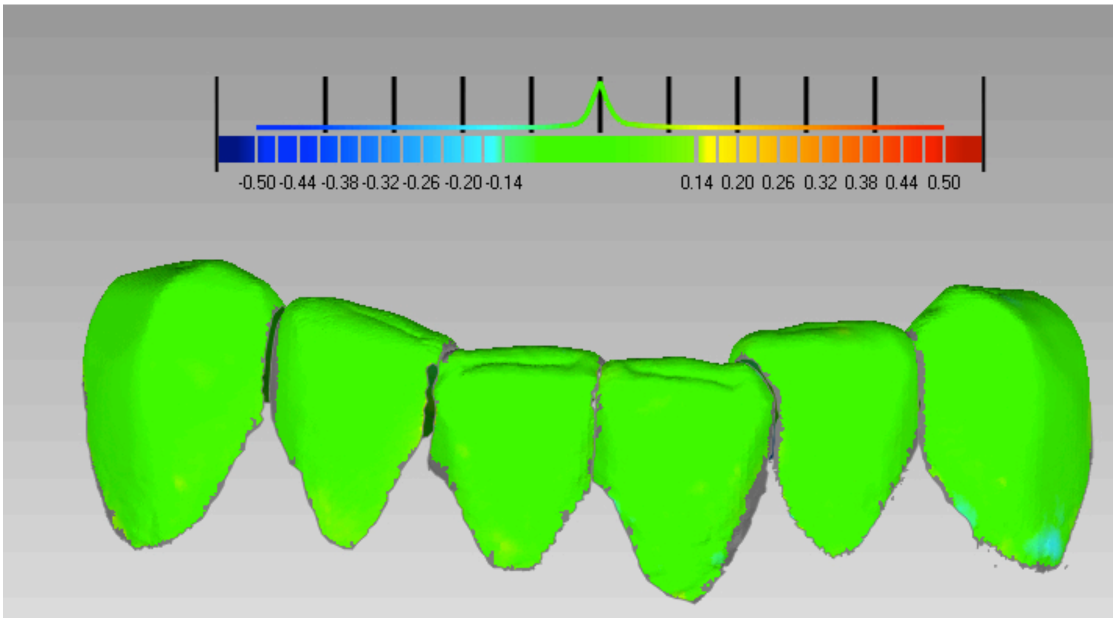


Figure 2.11: Merged STL file of individually best-fit registered lower anterior teeth for patient 'D' post merging and 3D deviation analysis.

2.2 Clinical Application

Once the 3D scanning system was calibrated and a 3D analysis approach established, the newly developed methodology was implemented clinically to quantify and monitor tooth wear in patients. However, there needs to be an understanding of the cohort of tooth wear patients from which participants can be recruited for this study. In this case, this patient cohort would comprise patients referred to Glasgow Dental Hospital and School by General Dental Practitioners for management of tooth wear. The understanding of this patient cohort would arise from identifying the demographics, patient-needs and expectations, diagnosed aetiology of tooth wear and the potential referral outcome. Once this is achieved, the next stage of ethical approval, patient recruitment and data-collection can initiate.

2.2.1 Survey of secondary care tooth wear referrals: demographics, reasons for concern and referral outcomes

The aim of this prospective survey was to provide a descriptive investigation of the patient cohort referred by General Dental Practitioners (GDPs) within Scotland to a secondary care setting for management of tooth wear and identify outcomes of the patient referral pathway. The survey would assist in identifying associations between certain patient factors, such as socio-economic status, gender, age, aetiology of tooth wear, treatment needs, and their referral to secondary care and whether they can be considered as tooth wear risk factors that can aid clinicians in diagnosing and appropriately managing tooth wear. Furthermore, the referral outcome would assist in further developing current secondary care referral pathways through potential improvements to referral system and/or GDP awareness.

2.2.1.1 Methods and materials

A prospective survey study was undertaken at Glasgow Dental Hospital and School (GDH&S) during April 1st 2010 to April 30th 2011. Ethical approval was provided by the West of Scotland Ethics Committee (10/S0709/59).

A tooth wear analysis questionnaire was formulated comprising 3 main sections (Appendix 1). Section A was completed by the screening auditor to collect patient demographic data and referral information. Section B was completed by the patient during their restorative specialist consultation and addressed patient-perception of their tooth wear condition. Section C was completed by the receiving consultant to record diagnosis and referral outcome. Only patients referred by GDPs solely for tooth wear management and assessment were included in this study. If there were other reasons for referral stated in the referral letter, then the patient was excluded from study participation. A convenience sample of one hundred and twenty four referrals was selected for inclusion in the study during the 12 month time period.

Prior to initial consultation, patient records were reviewed to identify patients referred by GDPs to GDH&S for tooth wear management. Once tooth wear referrals were identified and Section A of the questionnaire completed, the study questionnaire was attached to patients' records and completed by the patient and receiving restorative consultant. Included patients were reviewed by three restorative dentistry consultants at GDH&S. Questionnaires were then collected at the end of each new-patient consultation clinic for analysis.

In order to determine socio-economic deprivation level of referred patients, based upon the Scottish Index for Multiple Deprivation, Scottish Health Board quintiles (Board, 2012) (http://simd.scotland.gov.uk/publication-2012/) the patient post-code data was recorded.

Statistical analysis was performed using SPSS™ (release 18.0.0) and MiniTab™ (release 15.1.30.0.). In accordance with the determined sample size, a Fishers exact test was used to test differences between proportions.

2.2.2 Quantification of tooth wear *in-vivo* over a period of one year

2.2.2.1 Overview

The aim of this stage is to clinically monitor the progression of tooth wear in patients over a period of one year using the newly developed 3D scanning methodology. This stage involved: applying for ethical approval, patient recruitment, completion of a patient history questionnaire, acquirement of dental impressions from patients at baseline and after one year, scanning of poured impressions and 3D analysis of acquired scans to identify rate of tooth wear progression.

2.2.2.2 Ethical approval and participants' recruitment

Ethical approval was attained on the 14th of December 2010 from the West of Scotland Research and Ethics Committee, REC: 10/S0709/59, R&D Ref: GN10DN412.

Study participants were recruited thereafter through three Restorative Dentistry Consultants' New Patient clinics. The main investigator would initially screen patients' records on the day of consultation, identify potential participants and attach to their records a study package which consisted of: patient information sheet (Appendix 2), patient consent form (Appendix 3) and a patient history questionnaire (Appendix 4).

Study participants inclusion criteria was:

- Patients referred to GDH&S solely for management of tooth wear
- Consenting adults over the age of 16
- Patients requiring dental treatment that only involves monitoring of tooth wear condition and/or referral to hypnotherapy, as deemed appropriate by GDH&S reviewing consultant

Study participants exclusion criteria:

- Patients under the age of 16
- Patients referred to GDH&S for dental treatment/management not limited to tooth wear
- Reviewing GDH&S consultant treatment plan involves extensive restorative intervention or other invasive dental management modalities

Once the referred tooth wear patient has been reviewed by the Restorative Dentistry Consultant, the tooth wear condition and treatment needs of the patient are discussed with the main investigator. If the patient is deemed suitable for inclusion in the study, the main investigator would then approach the patient and discusses the study details, answer patient's queries and clarify any necessary information. The patient is then offered to participate in the tooth wear study, with emphasis that it is an observational study that would have no effect on their current or future treatment at GDH&S, regardless of their decision. If the patient accepts to participate in the study, they were asked to sign a consent form, of which they retained a copy, assigned a participant/patient identification number, and asked to complete a history questionnaire. Thereafter, appointments were made at GDH&S for initial impression taking of participants' dentition.

2.2.2.3 History questionnaire

The history questionnaire consisted of thirty-two questions covering the participant's medical and dental history, lifestyle factors, habits and diet (Appendix 4). The aim of the questionnaire was to assist in identifying the underlying aetiology of the observed tooth wear through positive findings in the questionnaire, and adapted from the findings of other studies (Ohayon et al., 2001, Dugmore and Rock, 2004a, Ganss et al., 2009, Bartlett et al., 2011b, El Aidi et al., 2011). The patients were advised to complete the questionnaire as objectively as possible, emphasising the anonymity of their data, as well as noting previous/historical presence of any of the conditions/factors/habits mentioned in the questionnaire, even if those conditions/factors/habits are no longer present.

2.2.2.4 Impression taking, cast-pouring and cast-scanning

During the initial visit, polyether impressions (Impregum™ Penta Soft – 3M™ ESPE™, MN, U.S.A) were taken of the participants' dentition and disinfected for 10 minutes (Perform®-ID, 3%, Schülke&Mayr GmbH, Norderstedt, Germany). Once impressions were retrieved, they were visually inspected for any errors, drags, air bubbles or voids. Once deemed satisfactory, the impressions were then poured within 24 hours in Suprastone die stone (ISO Type IV dental stone, KerrLab, CA., U.S.A). If impressions were unsatisfactory, with obvious errors, they were re-taken. The die stone was mixed according to manufacturer's recommendations and using vacuum mixing (EasyMix Vacuum Mixer, Bego™, Bremen, Germany) and vibration (Denstar-500, Denstar, Daegu, Korea) to minimise casting errors. Impressions were left for one hour prior to retrieval of the stone casts. The retrieved casts were then stored dry at room temperature (24˚C). At one month post-pouring, the casts were visually inspected for any obvious errors or discrepancies. If none were present, the maxillary and mandibular anterior teeth were contact-scanned on the cast replicas using the *incise*™ scanner. The resultant scan point-cloud, of the patient's casts functioned as a reference scan (T^O) against which future comparisons were made.

At one year following the initial visit, participants were recalled and their medical and dental history reviewed to identify any changes. Any changes to medical or dental history within the past year were recorded. Thereafter, the impression taking, cast pouring and scanning process were repeated as previously described. The resultant scan point-cloud (T^1) was then Best-fit registered against the reference scan, T^O, and 3D deviation analysis carried out.

2.3 Development of 3D tooth wear index

As part of this pilot study, the aim was to propose a novel 3D tooth wear index capable of accurately and objectively detecting the progression of tooth wear in patients over-time. Ideally, the index would be able to measure the depth and percentage of tooth surface area affected by tooth wear, appropriately detail the results and present them in a visually representative form demonstrating the true extent of the detected wear. Such presentation of results would aid both clinician and patient to understand the progression of tooth wear over the tooth wear monitoring period. Finally, the index would also be able to indicate whether the detected tooth wear was localised or generalised.

To do so, the 3D analysis data acquired from scanning participants' teeth in this study, detailing the progression of tooth wear *in-vivo* over a period of twelve months, was utilised and formed the basis for the newly proposed 3D tooth wear index, the dental surface profiling index (DSPI). The DSPI was formulated to classify both depth and surface area of tooth wear progression in patients. The Geomagic™ 3D deviation software analysis reports facilitated acquirement of the data. The data was then tabulated and statistical analysis was carried out to identify and group/classify varying depths and surface area distributions of tooth wear.

3. Results

This chapter details the findings from both sections of the pilot study: the calibration of 3D scanning system section and the clinical *in-vivo* application of the newly developed 3D scanning methodology section.

3.1 Calibration of 3D scanning system results

This section summarises the calibration results of the 3D scanning system, which comprises of the accuracy and precision of the 3D contact and non-contact scanners, the dimensional accuracy of dental casts produced from three types of impression materials and the dimensional stability of dental stone casts scanned at different time intervals.

3.1.1 Calibration of contact and non-contact 3D scanners

The coordinates of the seven sphere centres computed using the CMM and those computed using the laser scanner (FARO™) and dental stylus profilometer (*incise*™) were aligned and the distances between the seven corresponding sphere centres were calculated using MATLAB™ (Version R2012a) through Procuestes analysis. Mean errors and standard deviations were analysed and recorded (Tables 3.1 and 3.2). On average, SSM scanning times ranged between 20 minutes for the FARO™ arm laser scanner and 40 minutes for the incise™ contact scanner.

The coordinates of the seven SSM CAD sphere-centres, acquired through *incise*™ contact scanning (3 scans) and the FARO™ non-contact scanner (3 scans) were compared to the reference coordinates attained by the CMM. Measurement differences between both the contact and non-contact scan coordinates, and the reference coordinates demonstrated *incise*™ scanner accuracy to be 2.8µm with a precision/repeatability of ±0.8µm (StDev), while the FARO™ scanner demonstrated an accuracy of 82µm with a precision/repeatability of ±40µm (StDev). The data acquired was found to be normally distributed.

Table 3.1: Coordinate Measuring Machine (CMM) data (*n= 3* trials) for X, Y and Z coordinates of the Stainless Steel Model's (SSM) seven sphere centres and spheres' diameter. Measurements in millimetres.

Scan Trial	Centre X	Centre Y	Centre Z	Diameter
CMM 1	0.001	0	0.004	10.003
	5.002	14.007	0.022	10.005
	17.006	33.997	0.054	10.003
	27.497	43.994	0.164	10.007
	37.997	33.994	0.04	10.005
	49.994	13.996	0.037	10.005
	54.987	0	0.066	10.006
CMM 2	-0.001	0.001	0.003	10.004
	5.001	14.008	0.023	10.006
	17.006	33.998	0.059	10.004
	27.496	43.995	0.172	10.008
	37.996	33.995	0.049	10.007
	49.993	13.997	0.045	10.006
	54.986	0	0.074	10.007
CMM 3	0.001	0.001	-0.001	10.004
	5.003	14.008	0.019	10.006
	17.007	33.997	0.056	10.004
	27.497	43.994	0.171	10.007
	37.998	33.994	0.051	10.006
	49.994	13.996	0.052	10.006
	54.986	-0.001	0.083	10.007

Table 3.2: Statistical analysis of distance differences in X, Y and Z coordinates between measurements acquired by the Coordinate Measuring Machine and measurements acquired by *incise*™ and FARO scanners.

	Incise	Faro
Mean	0.0028	0.0823
Standard Error	0.0003	0.0075
Median	0.0028	0.0779
Mode	#N/A	#N/A
Standard Deviation	0.0008	0.0399
Sample Variance	0.0000	0.0016
Kurtosis	-0.4753	-0.4441
Skewness	-0.4695	0.5595
Range	0.0027	0.1464
Minimum	0.0011	0.0185
Maximum	0.0038	0.1648
Sum	0.0595	2.3031
Count	21.0000	28.0000
Confidence Level (95%)	0.0003	0.0155

3.1.2 Assessment of dimensional accuracy of dental casts

The mean diameter-difference between the SSM spheres (S^O) and the impression poured stone cast spheres, scanned at 24 hours post-pouring (S^{24}), was calculated for each type of impression material with a sample size of 15 spheres/material (Table 3.3 and Figure 3.1).

Alg poured casts demonstrated the greatest difference with a mean diameter-difference of -35µm ±64µm (StDev) effectively producing the most under-sized casts of all 3 types of impression materials. PE came second with -25µm ±29µm (StDev) difference and generally under-sized casts compared to S^O. PVS demonstrated the least mean-diameter difference, producing over-sized casts with a 12µm mean diameter difference. However, PVS also exhibited a larger variance of dimensional difference compared to PE, with a standard deviation of ±34µm (StDev).

A two-sample *t-test* did not demonstrate a statistically significant difference between Alg and PE (p= 0.544). However, the spheres' diameter differences of Alg and PE were significantly different compared to PVS at p= 0.036 and p= 0.006, respectively.

Table 3.3: Data of sphere diameter difference between CMM measurements of SSM and sphere diameter measurements on stone casts fabricated from different impression materials scanned at different time intervals. Alginate (Alg), Polyether (PE), Polyvinylsiloxane (PVS), 24 hour scan (24), 1 week (1WK) and one month (1MT). Letters A, B and C denote different samples. SSM spheres: LR1 (1st right sphere), LR2 (2nd right sphere), LL3 (3rd Left sphere), LL4 (4th left sphere) and LR3 (3rd right sphere). Measurements in millimetres.

Material/ Time+Sample	LR1	LR2	LL3	LL4	LR3
Alg 24 A	-0.148	0.005	0.042	0.039	0.04
Alg 24 B	-0.159	-0.051	0.032	-0.081	-0.045
Alg 24 C	-0.048	-0.044	-0.055	0.013	-0.065
Alg 48 A	-0.147	0.006	0.04	N/A	N/A
Alg 48 B	-0.163	-0.029	0.025	N/A	N/A
Alg48 C	-0.065	-0.04	-0.071	N/A	N/A
Alg 1WK A	-0.055	-0.08	-0.054	N/A	N/A
Alg1WK B	-0.141	0.01	0.048	N/A	N/A
Alg 1WK C	-0.045	-0.039	-0.033	N/A	N/A
Alg 1MT A	-0.133	0.045	0.046	N/A	N/A
Alg 1MT B	-0.12	0.014	0.054	N/A	N/A
Alg 1MT C	-0.04	-0.018	-0.012	N/A	N/A
PE 24 A	-0.035	-0.005	-0.062	0.028	-0.026
PE 24 B	-0.078	-0.023	-0.017	-0.022	-0.022
PE 24 C	-0.003	-0.005	-0.023	-0.077	-0.001
PE 48 A	-0.032	0.009	0.045	N/A	N/A
PE 48 B	-0.065	0.032	0	N/A	N/A
PE 48 C	-0.01	0.004	0	N/A	N/A
PE 1WK A	-0.033	0.014	-0.032	N/A	N/A
PE 1 WK B	-0.051	-0.023	0.019	N/A	N/A
PE 1WK C	0.007	0.028	0.01	N/A	N/A
PE 1MT A	-0.021	0.026	-0.02	N/A	N/A
PE 1 MT B	-0.049	-0.016	0.031	N/A	N/A
PE 1 MT C	0.014	0.039	0.024	N/A	N/A

Material/ Time+Sample	LR1	LR2	LL3	LL4	LR3
PVS 24 A	0.027	0.005	-0.004	-0.006	-0.021
PVS 24 B	-0.003	-0.008	0.012	0.006	0.0124
PVS 24 C	0.02	-0.026	0.004	0.04	0.118
PVS 48 A	0.012	0.002	-0.016	N/A	N/A
PVS 48 B	-0.011	0.017	0	N/A	N/A
PVS 48 C	0.012	-0.015	-0.002	N/A	N/A
PVS 1WK A	0.02	0.013	0.002	N/A	N/A
PVS 1WK B	-0.011	0.017	0.019	N/A	N/A
PVS 1WK C	0.019	-0.006	0.012	N/A	N/A
PVS 1MT A	0.037	0.025	0.019	N/A	N/A
PVS 1MT B	0.021	0.051	0.029	N/A	N/A
PVS 1MT C	0.037	0.002	0.024	N/A	N/A

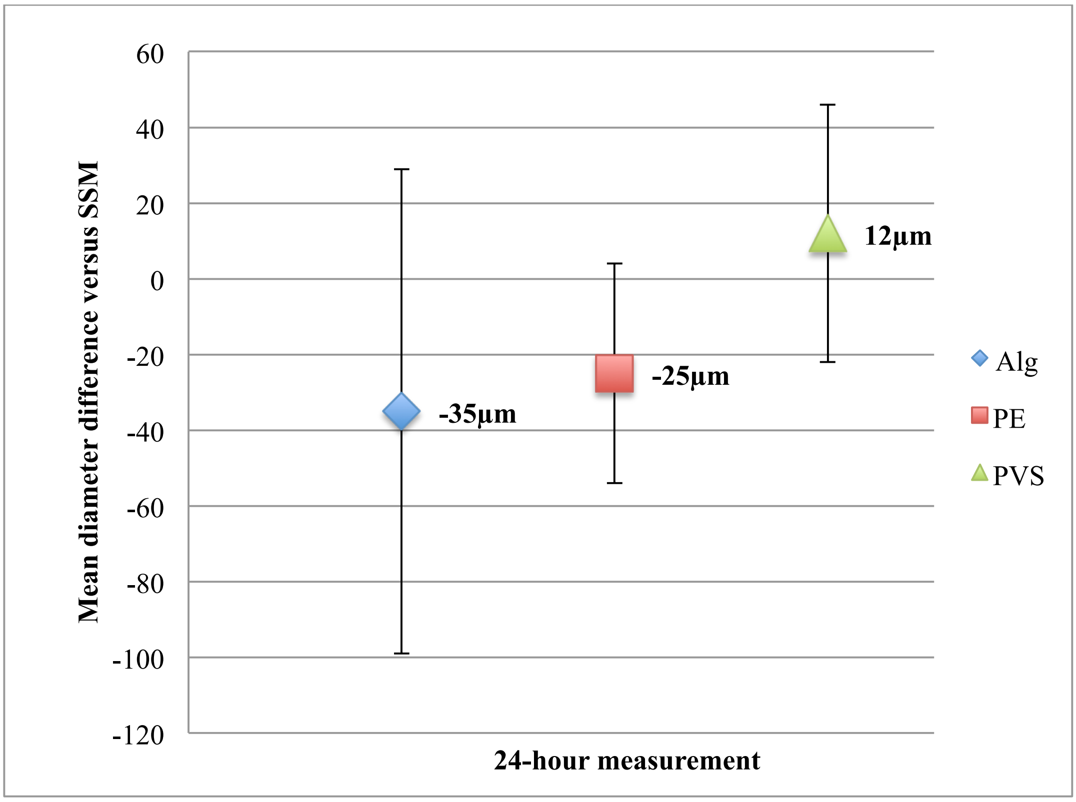


Figure 3.1: Dimensional accuracy (microns) of stone cast replicas (*n*= 15 for each impression material) measured at 24 hours post-pouring, scanned using the *incise*™ contact scanner and compared to Stainless Steel Model (SSM). Impression materials used were Alginate (Alg), Polyether (PE) and Polyvinylsiloxane (PVS).

3.1.3 Assessment of dimensional stability of dental casts

Sphere diameter comparisons for 27 samples were carried out between S^{24} and each of S^{48}, S^{WK} and S^{M} (Figure 3.2). At 48 hours post-pouring (S^{48}), spheres exhibited a mean diameter-difference of 7µm ±27µm (StDev), which translates, for the 10mm spheres, to a volume difference range of –0.2% - 0.8%. These differences were more pronounced at 1 week (S^{WK}), with the mean diameter difference increasing to 15µm ±15µm (StDev), volume difference of 0% - 0.9%, and at 1-month (S^{M}) to 27µm ±20µm diameter difference (StDev), volume difference of 0.2% - 1.4%, when compared to S^{24}. Hence, the stone spheres exhibited delayed expansion over a one -month period.

Further analysis using a one-sample *t-test* demonstrated no significant difference between S^{24} and S^{48} ($p = 0.212$). On the other hand, a significant difference was noted between S^{24} and both S^{WK} and S^{M}, at $p = 0.001$ and $p < 0.001$, respectively.

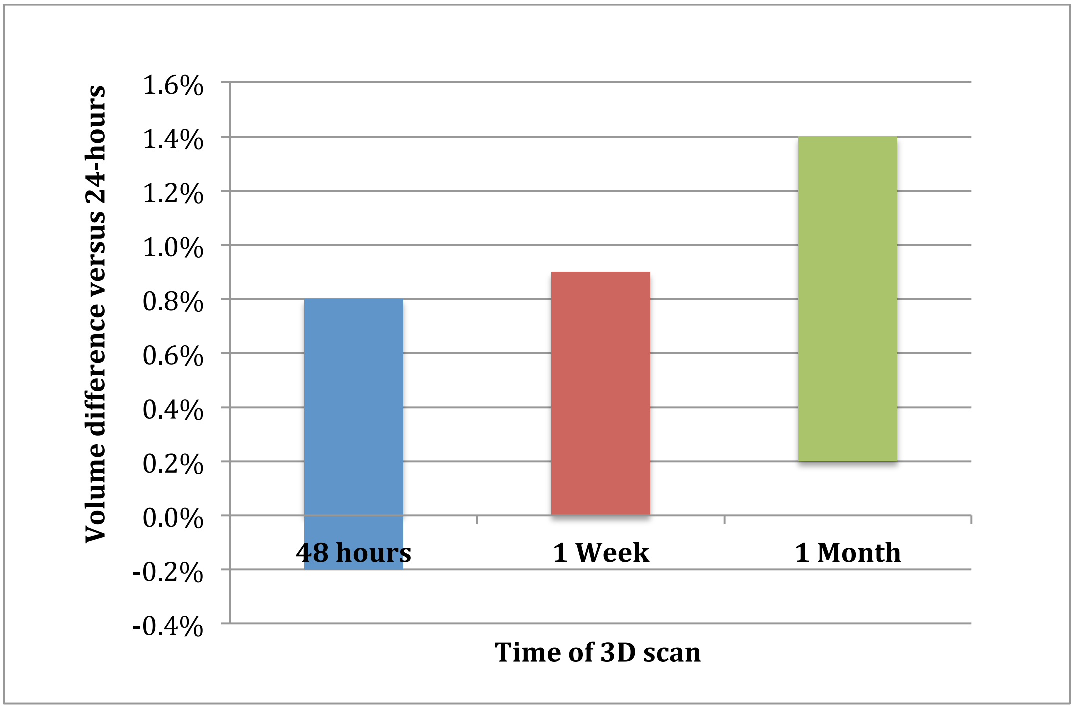


Figure 3.2: Range of dimensional change exhibited by cast spheres scanned at 48 hours (–0.2% - 0.8%), 1 week (0% - 0.9%), and 1 month (0.2% - 1.4%), post-pouring, (*n*=27). Results are expressed in percentage volume difference compared to 24-hour scans.

3.1.4 Overall 3D scanning system performance

The over-all scanning system's performance comprises of the uncertainties/ errors of the contact scanner, the dimensional accuracy of stone casts and the dimensional stability of stone casts at the time of scan.

The reference coordinates of the seven SSM spheres (S^O) acquired through the CMM were compared to those acquired through the *incise*™ scanner. Measurement differences demonstrated incise™ scanner accuracy to be at 2.8µm with a 95% confidence interval from 2.5 to 3.1µm.

Dimensional difference between reference S^O and polyether fabricated casts, scanned at 24-hours (S^{24}), demonstrated a dimensional accuracy of -25µm with 95% confidence interval of –39.7 to -10.3µm, and therefore initially producing slightly under-sized casts, compared to the SSM. Comparison between S^{24} and each of S^{48}, S^{WK} and S^M demonstrated continuous dimensional changes of stone casts over time. At 48 hours post-pouring, (S^{48}) spheres exhibited a difference of 7µm (95% C.I: -3.2 to 17.2µm) from S^{24}, while at S^{WK} and S^M dimensional differences, compared to S^{24}, where at 15µm (95% C.I: 9.3 to 20.7µm) and 27µm (95% C.I: 19.5 to 34.5µm) respectively.

The coverage interval (95% C.I) for each stage of the scanning methodology enabled us to calculate the overall 3D scanning system performance ($\alpha_{\mathbf{system}}$) through determining the overall standard error ($\mathbf{St_{error}}$) using the previously mentioned principle of propagation of error equation. Once the coverage interval was calculated, the $\alpha_{\mathbf{system}}$ was determined through calculating the difference between the lower and upper limits of the coverage interval (Table 3.4). Hence, the overall 3D scanning system performance when using the *incise*™ scanner to scan casts poured from polyether impressions and scanned at one month post-pouring is calculated through:

$$\textbf{Overall St}_{\textbf{err}} = \sqrt{\left(\frac{\partial_1}{\sqrt{n1}}\right)^2 + \left(\frac{\partial_2}{\sqrt{n2}}\right)^2 + \left(\frac{\partial_3}{\sqrt{n3}}\right)^2}$$

$$\textbf{Overall St}_{\textbf{err}} = \sqrt{\left(\frac{0.8}{\sqrt{21}}\right)^2 + \left(\frac{29}{\sqrt{15}}\right)^2 + \left(\frac{20}{\sqrt{27}}\right)^2} = \mathbf{8.4}$$

Coverage Interval (95% Confidence Interval) = ±1.96 **x** 8.4= **±16.5**

$$\alpha_{\text{system}} = (-16.5) \text{ to } 16.5 = \mathbf{33\mu m}$$

Consequently, the relative overall 3D scanning system performance (α_{relative}) when comparing two individual *incise*™ scans taken of casts poured from polyether impressions and scanned at one-month post-pouring is:

$$\alpha_{\text{relative}} = 33\mu m \times 2 = \mathbf{66\mu m}$$

Table 3.4: Overall 3D scanning system performance (α_{system}), when using polyether-poured casts, and 3D scanning the casts at different time frames. Table includes the mean, the 3D scanning system coverage interval (95% C.I) lower and upper limits and the α_{system} at each time frame. To determine α_{system} at a specific time frame, the principle of propagation of errors was used to calculate the overall standard error that accounts for the uncertainties/ errors of: 3D scanning, casts at 24 hours and casts at a specific time frame (48 hours, 1 week or 1 month). The overall standard error is then used to calculate the coverage interval and consequently the α_{system} at a specific time frame.

Time	Mean (µm)	Coverage interval lower limit (µm)	Coverage interval upper limit (µm)	α_{system}
3D Scanner	2.8	2.5	3.1	0.6µm
24 hours	-22.2	-36.9	-7.5	28.5µm
48 hours	-15.2	-33.1	2.7	35.8µm
1 week	-7.2	-22.9	8.5	31.4µm
1 month	4.8	-11.7	21.3	33µm

3.2 Clinical findings

This section details the findings of the clinical component of the study. This clinical component comprises of two subsections: findings from the survey of secondary tooth wear referrals by general dental practitioners (GDPs) to Glasgow Dental Hospital and School (GDH&S) and findings from the questionnaire and the *in-vivo* 3D analysis of tooth wear progression in patients over a period of twelve months participating in the study.

3.2.1 Survey of secondary tooth wear referrals findings

One hundred and twenty four patient referrals for tooth wear were identified and included in this pilot study. Eighty questionnaires were completed by patients for part B and eighty-three questionnaires completed by the reviewing consultant for part C. The over-all return-rate of included tooth wear study referrals was 67% (n=83).

There was a significant difference (*p=0.001)* between the number of male and female patients referred for tooth wear management, with 72% (*n*= 89*)* of toothwear referrals being male compared to 28% (*n*= 35) female. A greater number of referred patients (59%) inhabited the most deprived areas (quintiles 1 and 2, according to the Scottish Index for Multiple Deprivation), this being significantly higher (*p=0.002*) than those inhabiting the least deprived areas (Table 3.5). Attrition was mentioned as the underlying aetiological cause of tooth wear in 40% (*n*= 50) of GDP referral letters, followed by erosion (15% n= 18) and 10% (*n*= 12) identifying a combination of attrition and erosion. There was no mention of the aetiological cause of tooth wear in 35% (*n*= 44) of GDP referral letters. In ninety-eight percent (*n*= 121) of patient referrals, no dental study casts were sent with the GDP referral. Seventy-two per cent of referred patients were between the ages of 31 and 63, which represented a significant difference (*p=0.001*) when compared to other age groups (19-30 and 64 -79) within the study (Table 3.6).

The percentage of patients previously aware of their tooth wear condition for less than six years was significantly higher (*p=0.007, n*= 49) at 61% compared to those aware of the condition for 6 - 10 years (*n*= 17, 21%) or over 10 years (*n*= 14, 18%). The number of tooth wear patients either concerned or severely concerned by their tooth wear condition was significantly greater (*n*= 71, *p=0.001*) than those not concerned by the condition (*n*= 9, 11%,). Aesthetics was the principal reason for concern in 54% of study patients (95% C.I= 40 - 60%, *p=0.001)* (Table 3.7). Fewer patients reported sensitivity or function as their main reasons for concern at 25% and 12% respectively.

Attrition was diagnosed by Restorative specialists as the primary aetiological cause of tooth wear in 51% of referrals (*n=42)*. This was significantly higher (*p=0.001*) than tooth wear diagnosed as a result of erosion (17%, *n=14)* or a combination of attrition and erosion (32%, *n=27)*. Seventy-eight patients, representing 92% of returned referral questionnaires, were assessed as not requiring specialist treatment intervention and were instead returned to their GDP with a treatment plan, referred for a course of hypnotherapy to address underlying bruxism behaviour or seen for further review within the secondary care setting to monitor tooth wear progression (Table 3.8).

Table 3.5: Distribution of referred tooth wear patients within most deprived to least deprived categories, using SIMD quintiles based on patients' postcode data.

SIMD quintile	Number of referrals, *n=124*
1 (most deprived)	38 (31%)
2	26 (26%)
3	21 (17%)
4	10 (8%)
5 (least deprived)	14 (11%)
Blank (information not given)	15 (12%)

Table 3.6: Distribution of tooth wear referrals based on age groups.

Age group (years)	Number of referrals, *n=124*
19 – 30	20 (16%)
31 – 41	31 (25%)
42 – 52	31 (25%)
53 – 63	27 (22%)
64 – 79	15 (12%)

Table 3.7: Distribution of patient concerns when requesting a secondary care referral for their tooth wear. Main reason for concern (MRC).

MRC	Males, *n=57*	Females, *n=23*	Total, *n=80*
Aesthetics	35 (61%)	8 (35%)	43 (54%)
Function	10 (18%)	0	10 (12%)
Sensitivity	7 (12%)	13 (57%)	20 (25%)
Other	5 (9%)	2 (9%)	7 (9%)

Table 3.8: Tooth wear patient referral outcomes at GDH&S. General Dental Practitioner (GDP).

Referral outcome	Number of referrals(*n=83)*
Return to GDP	39 (47%)
Hypnotherapy	23 (28%)
Review	14 (17%)
Secondary care treatment	7 (8%)

3.2.2 Clinical findings of questionnaire and 3D analysis over a period of one year

Eleven patients (n= 11/30) were available at 12 months recall; 6 males and 5 females (mean age: 47) (Table 3.9). All patients (n=11) indicated positive attrition risk factors, including: grinding, clenching, and nail and pencil biting. Seventy three per cent of patients (n= 8) were aware of their tooth wear condition within the past 5 years. The majority of patients (n= 9/11) indicated the presence of multifactorial risk factors of tooth wear, with five patients presenting a combination of attrition, erosion and abrasion risk factors; three patients with attrition and abrasion; and one patient with attrition and erosion risk factors. Sixty-four per cent of patients (n=7/11) indicated positive mental health risk factors, which included: stressful or extremely stressful lifestyle, depression, and/or anti-depressive medication. Due to the small sample size, statistical analysis was not possible; hence, results indicate trends within the study sample rather than statistically significant results that are population-representative.

The overall system performance (α_{system}), which indicates the maximum possible accuracy of the formulated scanning methodology, was demonstrated to range between 28.5µm - 35.8µm. This α_{system} is based on taking polyether impressions, pouring them in Type IV dental stone and scanning the stone casts using the *incise*™ scanner at different time intervals post-pouring. However, even with the various safe-guard mechanisms of: inspecting the acquired impression and the resultant poured cast, preparing the scan prior to Best-fit registration and registration of teeth on an individual basis, it is not unreasonable to expect some surface irregularities to be present in the scan data that were not visually detectable initially and which might lead to anomalies during best-fit registration and/or 3D deviation analysis. Furthermore, the overall system performance is based on measurements acquired from scanning the SSM smooth, geometrical spheres that possess a simple topography when compared to the complex morphology of teeth. Additionally, the relative system performance ($\alpha_{relative}$) needs to be considered when monitoring tooth wear progression at different epochs, as it accounts for the system accuracy when comparing two scans. The $\alpha_{relative}$ is twice the overall system performance and in this study demonstrated to be 66µm (when scanning casts at 1-month post-pouring using the *incise*™ scanner). Hence, when all the aforementioned factors are taken into account (the potentially undetectable replication and/or scanning irregularities, the detected α_{system} at ideal conditions and $\alpha_{relative}$) the decision to implement a scanning safety margin of 140µm at which tooth wear can be detected *in-vivo* using the developed methodology which is approximately twice the $\alpha_{relative}$, was deemed logistically prudent and clinically acceptable.

Once the history questionnaire was completed by the patients, polyether impressions were taken of patients upper and lower dentition on initial visit T^O and at twelve-months recall T^1. Impressions taking, pouring, *incise*™ cast-scanning and 3D analysis was carried out as previously detailed in the methodology. 3D analysis reports were then generated and exported (Table 3.10 and 3.11). Tooth wear progression over a period of twelve months per tooth per patient was extracted, tabulated and analysed (Table 3.12 and Figure 3.3).

Findings of 3D analysis of tooth wear progression over a period of 12 months demonstrated that:

- All patients (*n*=11) experienced either 260- 380µm or 380 - >500µm of tooth wear depth, in one or more of their anterior teeth, over a period of 12 months, when ≥0.1% tooth wear affected surface area was considered.
- 92% of all anterior teeth (*n*=120/130) demonstrated tooth wear of ≥140µm of depth over a period of one year. Within the anterior teeth presenting with tooth wear, 79% of those anterior teeth (*n*= 95/120) demonstrated ≥260µm of tooth wear depth, and 31% (*n*= 37/120) demonstrated ≥ 380µm tooth wear depth.
- The total surface area affected by tooth wear in 53% of teeth (*n*=64/120) was between 0.1% - 2% of tooth surface area (Table 3.13).
- The total surface area affected by tooth wear in sixty-eight percent of teeth (*n*= 82/120) was between 0.1% - 4%, while eighteen percent of teeth (*n*= 22/120) demonstrated tooth wear surface area >4% - 8% and thirteen percent (*n*= 16/120) demonstrated >8% tooth wear of tooth surface area (Figure 3.3).
- Mean surface area of tooth wear was 3.6% (St.Dev: ±4%), *n*=120.
- Median surface area of tooth wear was 2% (*n*=120).
- Upper central incisors were the tooth group demonstrating the largest number of teeth presenting with 380 - >500µm tooth wear depth (32%, *n*= 12/37), followed by upper canines (30%, *n*=11/37) (Table 3.14).

- Upper central incisors were the tooth group demonstrating the greatest depth of tooth wear (260 - >500µm) with 20% (*n*= 19/95), followed by lower canines, 18%, (*n*=17/95) (Table 3.14).
- Lower central incisors were the tooth group demonstrating largest group of teeth with 260- 380µm of tooth wear depth-affected teeth (26%, *n*=15/58), followed by lower laterals (21%, *n*=12/58) (Table 3.14).
- Upper central incisors demonstrated the greatest mean total surface area of tooth wear (140 - >500µm) amongst all tooth groups, with mean tooth wear distribution of 6.1% (StDev: ±5%) (Table 3.15).

Table 3.9: Positive findings from patient history questionnaire covering medical, dental, dietary and lifestyle risk factors of tooth wear. Duration of awareness of tooth wear condition (DOA), Intrinsic erosion (Int. Erosion), Extrinsic Erosion (Ext. Erosion), Parafunctional habits (Para. habits).

Patient	Gender	Age	DOA	Para. habits	Int. Erosion	Ext. Erosion	Abrasion	Mental Health
A	M	69	>10yrs	Yes	Yes	Yes	Yes	Yes
B	M	43	1-5yrs	Yes	No	No	No	Yes
C	F	56	1-5yrs	Yes	No	No	Yes	Yes
D	M	26	1-5yrs	Yes	Yes	Yes	Yes	Yes
E	F	31	1-5yrs	Yes	No	Yes	Yes	No
F	M	50	1-5yrs	Yes	No	No	Yes	No
G	F	56	>10yrs	Yes	Yes	No	No	Yes
H	F	48	<1yr	Yes	No	Yes	Yes	No
I	M	55	1-5yrs	Yes	No	Yes	Yes	Yes
J	M	28	1-5yrs	Yes	Yes	No	No	Yes
K	F	49	1-5yrs	Yes	No	No	Yes	No

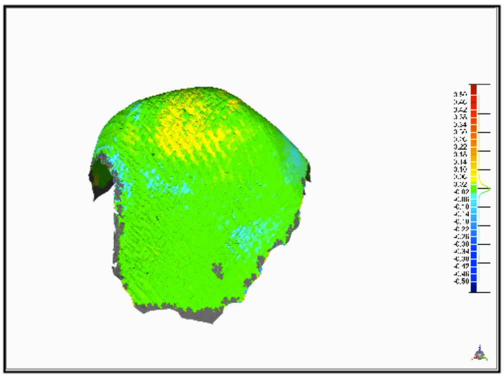
Table 3.10: Example of a 3D deviation analysis report generated by Geomagic Qualify™ and comparing scans of a single tooth initially (reference) and after one year (test). Report demonstrates distribution of dimensional changes (Deviation Distribution) in the form of a table, a histogram and a colour-coded map. The colour-coded map is at 40µm increment scale (20µm to -20µm (green), -20µm to -60µm, -60µm to -100µm, etc.). Majority of tooth wear between -20µm to -60µm.

3D Comparison Results

Reference Model	[redacted]
Test Model	[redacted]
No. of Data Points	15230
# Outliers	101

Tolerance Type	3D Deviation
Units	mm
Max. Critical	0.50
Max. Nominal	0.02
Min. Nominal	-0.02
Min. Critical	-0.50

Deviation	
Max. Upper Deviation	0.38
Max. Lower Deviation	-0.38
Average Deviation	0.02 / -0.02
Standard Deviation	0.05



Deviation Distribution

>=Min	<Max	# Points	%
-0.50	-0.46	0	0.00
-0.46	-0.42	0	0.00
-0.42	-0.38	5	0.03
-0.38	-0.34	40	0.26
-0.34	-0.30	28	0.18
-0.30	-0.26	19	0.12
-0.26	-0.22	35	0.23
-0.22	-0.18	39	0.26
-0.18	-0.14	40	0.26
-0.14	-0.10	41	0.27
-0.10	-0.06	55	0.36
-0.06	-0.02	1653	10.85
-0.02	0.02	11270	74.00
0.02	0.06	1600	10.51
0.06	0.10	117	0.77
0.10	0.14	59	0.39
0.14	0.18	66	0.43
0.18	0.22	39	0.26
0.22	0.26	35	0.23
0.26	0.30	36	0.24
0.30	0.34	31	0.20
0.34	0.38	20	0.13
0.38	0.42	2	0.01
0.42	0.46	0	0.00
0.46	0.50	0	0.00

Out of Upper Critical		0	0.00
Out of Lower Critical		0	0.00

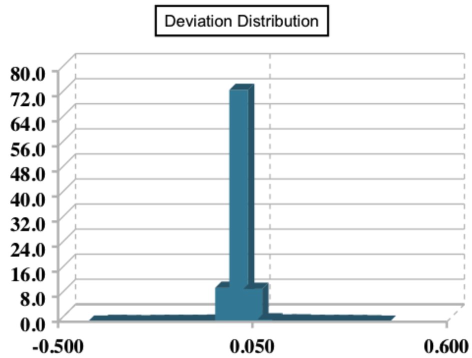


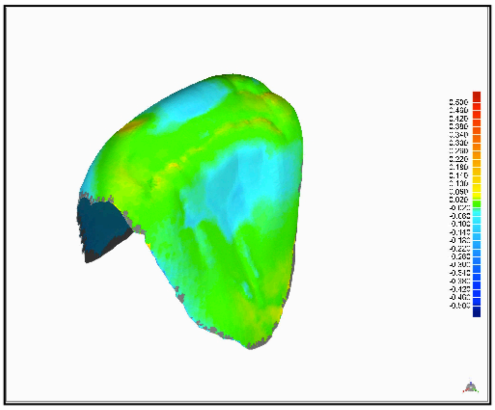
Table 3.11: Example of a 3D deviation analysis report generated by Geomagic Qualify™ and comparing scans of a single tooth initially (reference) and after one year (test). Report demonstrates distribution of dimensional changes (Deviation Distribution) in the form of a table, a histogram and a colour-coded map. The colour-coded map is at 40µm increment scale (20µm to -20µm (green), -20µm to -60µm, -60µm to -100µm, etc.). Majority of wear between -20µm and -180µm.

3D Comparison Results

Reference Model	[redacted]
Test Model	[redacted]
No. of Data Points	20091
# Outliers	56

Tolerance Type	3D Deviation
Units	mm
Max. Critical	0.500
Max. Nominal	0.020
Min. Nominal	-0.020
Min. Critical	-0.500

Deviation	
Max. Upper Deviation	0.422
Max. Lower Deviation	-0.405
Average Deviation	0.018 / -0.052
Standard Deviation	0.053



Deviation Distribution

>=Min	<Max	# Points	%
-0.500	-0.460	0	0.000
-0.460	-0.420	0	0.000
-0.420	-0.380	3	0.015
-0.380	-0.340	3	0.015
-0.340	-0.300	9	0.045
-0.300	-0.260	17	0.085
-0.260	-0.220	48	0.239
-0.220	-0.180	145	0.722
-0.180	-0.140	621	3.091
-0.140	-0.100	1223	6.087
-0.100	-0.060	2669	13.285
-0.060	-0.020	5011	24.942
-0.020	0.020	9007	44.831
0.020	0.060	1169	5.819
0.060	0.100	59	0.294
0.100	0.140	21	0.105
0.140	0.180	26	0.129
0.180	0.220	19	0.095
0.220	0.260	14	0.070
0.260	0.300	12	0.060
0.300	0.340	6	0.030
0.340	0.380	4	0.020
0.380	0.420	4	0.020
0.420	0.460	1	0.005
0.460	0.500	0	0.000

Out of Upper Critical	0	0.000
Out of Lower Critical	0	0.000

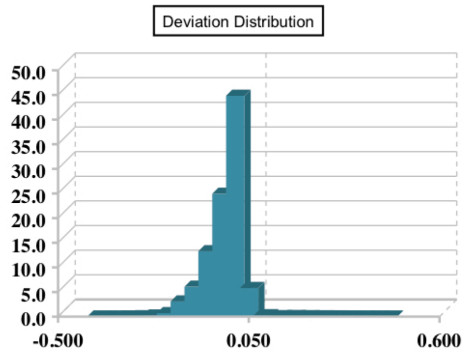


Table 3.12: Percentage of surface area affected by different depths of detected dimensional changes (tooth wear) in dentition present in eleven study participants (*n*= 130 teeth) over a period of one year, measured through 3D deviation analysis using Geomagic Qualify™. Letters denote participant, numbers denote FDI tooth number. Depth measurements in microns, affected surface area in percentage.

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
A 13	5.9%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.1%
A 12	5.8%	5.1%	5.0%	2.3%	0.4%	0.3%	0.0%	0.0%	0.0%	18.9%
A 11	3.1%	0.7%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	4.2%
A 21	6.10%	0.90%	0.2%	0.1%	0.1%	0.10%	0.10%	0.0%	0.0%	7.6%
A 22	2.4%	3.0%	0.6%	0.4%	0.3%	0.1%	0.0%	0.0%	0.0%	6.8%
A 23	4.0%	0.2%	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%	0.0%	4.3%
A 33	6.5%	0.8%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	7.6%
A 32	1.0%	0.4%	0.3%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	1.9%
A 41	8.60%	3.50%	0.10%	0.02%	0.0%	0.0%	0.0%	0.0%	0.0%	12.2%
A 42	4.30%	8.10%	6.10%	0.60%	0.30%	0.09%	0.07%	0.02%	0.01%	19.6%
A 43	6.3%	2.6%	0.4%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	9.5%
B 13	0.4%	0.3%	0.3%	0.2%	0.2%	0.1%	0.1%	0.4%	0.0%	2.0%
B 12	1.9%	1.2%	1.0%	1.4%	1.0%	0.4%	0.0%	0.0%	0.0%	6.9%
B 11	2.1%	2.1%	1.9%	2.1%	1.3%	1.0%	0.8%	0.7%	0.1%	12.1%
B 21	2.3%	1.5%	1.2%	0.7%	0.5%	0.5%	0.3%	0.2%	0.2%	7.3%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
B 22	1.2%	0.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%
B 23	0.8%	0.8%	0.5%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	2.7%
B 33	1.2%	1.3%	1.2%	1.1%	1.0%	1.1%	1.1%	1.0%	0.6%	9.6%
B 32	0.3%	0.1%	0.0%	0.1%	1.0%	0.0%	0.0%	0.0%	0.0%	1.5%
B 31	2.3%	0.3%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	2.8%
B 41	0.2%	0.0%	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.5%
B 42	1.5%	0.8%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	2.7%
B 43	0.45%	0.39%	0.30%	0.26%	0.29%	0.26%	0.22%	0.02%	0%	2.2%
C 13	0.3%	0.3%	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%	0.0%	1.7%
C 12	0.2%	0.2%	0.2%	0.2%	0.1%	0.2%	0.1%	0.0%	0.0%	1.2%
C 11	1.5%	1.4%	0.8%	0.9%	0.9%	0.7%	0.6%	0.3%	0.0%	7.1%
C 21	0.8%	0.8%	0.8%	0.6%	0.4%	0.3%	0.4%	0.2%	0.0%	4.3%
C 22	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
C 23	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
C 33	0.3%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.7%
C 32	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
C 31	0.2%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
C 41	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
C 42	0.2%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
C 43	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
D 13	0.3%	0.2%	0.1%	0.1%	0.1%	0.0%	0.1%	0.1%	1.0%	2.0%
D 12	0.6%	0.5%	0.5%	0.4%	0.3%	0.2%	0.0%	0.0%	0.0%	2.5%
D 11	0.3%	0.3%	0.1%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	1.0%
D 21	2.6%	1.1%	0.4%	0.1%	4.0%	0.0%	0.0%	0.0%	0.0%	8.4%
D 22	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
D 23	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.8%
D 33	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
D 32	0.8%	0.8%	0.9%	1.2%	1.2%	1.3%	2.0%	0.4%	0.0%	8.6%
D 31	0.6%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%
D 41	0.1%	0.0%	0.1%	0.0%	0.2%	0.1%	0.0%	0.0%	0.0%	0.5%
D 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
D 43	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%	0.0%	0.0%	0.0%	1.1%
E 13	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E 12	1.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%
E 11	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
E 21	0.5%	0.4%	0.3%	0.3%	0.2%	0.2%	0.0%	0.0%	0.0%	1.9%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
E 22	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E 23	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E 33	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E 32	0.9%	0.5%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%
E 31	2.3%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%
E 41	0.5%	0.1%	0.1%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.7%
E 42	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E 43	1.3%	1.7%	1.0%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%
F 13	0.6%	0.2%	0.2%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	1.4%
F 12	0.5%	0.3%	0.1%	0.0%	0.0%	3.0%	0.0%	0.0%	0.0%	3.9%
F 11	8.3%	1.8%	1.2%	0.6%	0.2%	0.1%	0.1%	0.1%	0.0%	12.4%
F 21	1.8%	1.4%	1.2%	1.1%	1.1%	1.2%	1.2%	1.2%	0.3%	10.5%
F 22	2.2%	0.5%	0.2%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	3.3%
F 23	1.2%	0.3%	0.2%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	2.1%
F 33	0.8%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%
F 32	3.0%	1.2%	0.5%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%
F 31	0.7%	0.5%	0.7%	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	2.3%
F 41	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
F 42	1.7%	0.6%	0.3%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	2.8%
F 43	0.5%	0.4%	0.4%	0.4%	0.3%	0.4%	0.3%	0.3%	0.3%	3.3%
G 13	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
G 12	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
G 11	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
G 21	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
G 22	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
G 23	0.4%	0.3%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	1.1%
G 33	0.2%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
G 32	0.5%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	1.0%
G 31	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%
G 41	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
G 42	0.6%	0.4%	0.3%	0.3%	0.3%	0.0%	0.0%	0.0%	0.0%	1.9%
G 43	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
H 13	0.6%	0.5%	0.4%	0.3%	0.2%	0.2%	0.2%	0.1%	0.0%	2.5%
H 12	1.3%	1.2%	1.1%	1.0%	0.6%	0.6%	0.7%	0.7%	0.6%	7.8%
H 11	2.7%	2.5%	3.0%	2.7%	3.1%	2.1%	1.3%	0.9%	0.5%	18.8%
H 21	1.4%	1.1%	1.0%	0.7%	0.6%	0.5%	0.4%	0.3%	0.4%	6.4%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
H 22	1.2%	1.4%	0.9%	0.9%	0.7%	0.8%	0.1%	0.0%	0.0%	6.0%
H 23	0.3%	0.1%	0.1%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	1.3%
H 33	0.3%	0.2%	0.2%	0.2%	0.2%	0.1%	0.2%	0.1%	0.0%	1.5%
H 32	2.0%	0.7%	0.8%	0.6%	0.3%	0.1%	0.0%	0.0%	0.0%	4.5%
H 31	1.5%	1.3%	1.1%	0.7%	1.0%	0.1%	0.0%	0.0%	0.0%	5.7%
H 41	2.1%	1.8%	1.2%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	5.5%
H 42	0.6%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%
H 43	2.5%	4.3%	1.5%	1.1%	0.3%	0.2%	0.2%	0.1%	0.0%	10.1%
I 13	5.5%	1.8%	0.4%	0.4%	0.1%	0.1%	0.1%	0.1%	0.0%	8.5%
I 12	1.0%	0.3%	0.3%	0.3%	0.1%	0.0%	0.0%	0.0%	0.0%	2.0%
I 11	2.8%	2.1%	2.2%	1.2%	0.3%	0.1%	0.0%	0.0%	0.0%	8.7%
I 21	2.1%	1.9%	1.3%	0.4%	0.3%	0.1%	0.0%	0.0%	0.0%	6.1%
I 23	0.7%	0.5%	0.3%	0.3%	0.2%	0.2%	0.1%	0.1%	0.0%	2.4%
I 33	4.3%	1.8%	0.6%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	7.3%
I 32	5.1%	1.8%	0.5%	0.4%	0.1%	0.1%	0.0%	0.0%	0.0%	8.0%
I 31	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
I 41	2.6%	1.0%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	3.9%
I 42	7.8%	1.4%	0.3%	0.2%	0.2%	0.2%	0.1%	0.0%	0.0%	10.1%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
I 43	1.8%	0.5%	0.3%	0.2%	0.3%	0.1%	0.2%	0.0%	0.0%	3.4%
K 13	0.2%	0.1%	0.2%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	1.1%
K 12	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%
K 11	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	1.2%
K 21	0.6%	0.2%	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	1.3%
K 22	0.2%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.5%
K 23	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.7%
K 33	0.2%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
K 32	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%
K 31	0.4%	0.5%	0.2%	0.2%	0.3%	0.1%	0.0%	0.0%	0.0%	1.7%
K 41	0.2%	0.2%	0.2%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.7%
K 42	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.5%
K 43	0.2%	0.2%	0.1%	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	0.8%
L 13	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
L 12	0.8%	1.0%	0.9%	0.9%	0.3%	0.0%	0.0%	0.0%	0.0%	3.8%
L 11	1.8%	1.9%	1.3%	0.6%	0.4%	0.2%	0.1%	0.1%	0.0%	6.4%
L 21	0.4%	0.4%	0.4%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	1.5%
L 22	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%

Participant and Tooth number	140-180 µm	180-220 µm	220-260 µm	260-300 µm	300-340 µm	340-380 µm	380-420 µm	420-460 µm	460->500 µm	Total
L 23	0.3%	0.3%	0.2%	0.1%	0.2%	0.3%	0.0%	0.0%	0.0%	1.3%
L 33	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
L 32	0.4%	0.6%	0.4%	0.4%	0.1%	0.0%	0.0%	0.0%	0.0%	2.0%
L 31	2.7%	2.4%	1.8%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	8.3%
L 41	1.3%	0.3%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	1.8%
L 42	0.8%	0.7%	0.6%	0.5%	0.5%	0.1%	0.0%	0.0%	0.0%	3.1%
L 43	0.4%	0.2%	0.2%	0.1%	0.2%	0.1%	0.0%	0.0%	0.0%	1.3%

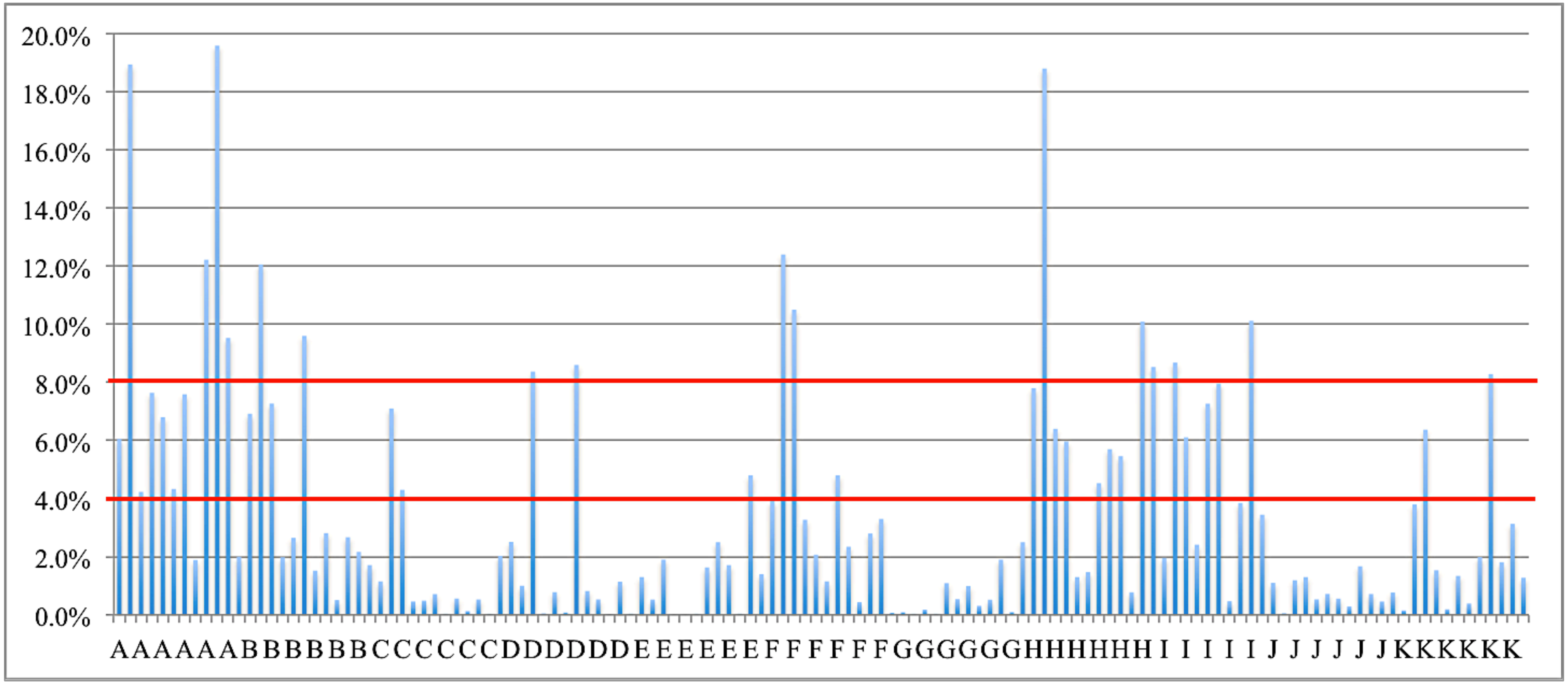


Figure 3.3: Overall total surface area (Grade1+2+3) of detected tooth wear for all teeth (*n*=130), per patient (*n*=11), and measured through 3D deviation analysis carried-out in Geomagic Qualify™. Letters denote individual teeth per patient. Tooth wear was detected in 120 teeth. Surface area of tooth wear was between 0.1% - 4% in sixty-eight percent of teeth (*n*= 82/120), >4% - 8% in eighteen percent of teeth (*n*=22/120) and >8% in thirteen percent of teeth (*n*= 16/120).

Table 3.13: Percentage of teeth demonstrating a surface area affected by tooth wear less than or equal to 2% of total tooth surface area.

Percentage of tooth surface area	Percentage of teeth affected
0.1% - ≤0.5%	21% (*n*=25/120)
0.1% - ≤1%	34% (*n*=36/120)
0.1% - ≤1.5%	48% (*n*=50/120)
0.1% - ≤2%	53% (*n*=64/120)

Table 3.14: Distribution of teeth according to depth of measured tooth wear, after one year recall, and demonstrating 260-380 µm or 380 - >500µm depth of tooth wear (*n*= 95). Teeth divided into six groups: UC (Upper Central-incisors); UL (Upper Lateral-incisors); UCa (Upper Canines); LC (Lower Central-incisors); LL (Lower Lateral-incisors) and LCa (Lower Canines).

Tooth Group	260-380 µm	380 - >500µm	260- >500µm
UC	7	12	19
UL	10	3	13
UCa	5	11	16
LC	15	0	15
LL	12	3	15
LCa	9	8	17
Total number of teeth	58	37	95

Table 3.15: Mean percentage of surface area affected by tooth wear (Grades 1+2+3) per tooth group. Teeth presenting tooth wear are divided into six groups: UC (Upper Central-incisors); UL (Upper Lateral-incisors); UCa (Upper Canines); LC (Lower Central-incisors); LL (Lower Lateral-incisors) and LCa (Lower Canines). No tooth wear was detected in 10 teeth. Total number of 3D analysed teeth (*n*=130): number of teeth with detected tooth wear (*n*= 120) and teeth with no detected tooth wear (*n*= 10).

Tooth Group	Mean	St.Dev	Total
UC	6.1%	5%	21
UL	3.6%	5%	19
UCa	2.1%	2%	20
LC	2.5%	3%	21
LL	4%	5%	19
LCa	3.3%	4%	20

4. Discussion

This chapter will discuss the methodology employed in this pilot study and findings deduced from it. The chapter comprises of two subsections: calibration of 3D scanning system and the clinical *in-vivo* application of the newly developed methodology aimed at quantifying tooth wear in patients over a period of twelve months.

4.1 Calibration of 3D scanning system

The results of this study demonstrate a higher accuracy and precision of the dental stylus profilometer (*incise*™) compared to the non-contact laser scanner (FARO™). The use of a CMM as a reference-standard measuring tool ascertains that all the coordinates measured on SSM are accurate to (2.2+3L/1000)µm, as dictated by the ISO 10360-2:2009. This novel testing method can be used to independently calibrate other scanners in the future and identify their accuracy and precision.

The SSM consisted of seven spheres, placed at different heights, embedded in a horseshoe-shaped base. The use of calibrated spheres to assess the accuracy and precision of contact scanners remains the gold-standard methodology for assessment as indicated by ISO10360-part 4 (1994). On the other hand, it can be argued that the accuracy of scanning the simple geometry of a sphere will be challenged when scanning the more complex morphology of teeth, ergo, calibration of a model with teeth would be a more accurate and clinically relevant methodology. However, currently the greatest accuracy for scanning remains contact profilometery using a CMM that relies on highly –accurate and time-consuming probe scanning of a specific number of points on the surface of an artefact, measuring their coordinates in the X, Y and Z axes and then using these measured points to generate a CAD model of the artefact. Attempting to map-out the morphology of a dental cast to achieve a 1-2µm accurate 3D scan of a complete dentition would be logistically laborious and extremely time consuming, with potential scanning time extending for days using a dedicated CMM, which is impractical and unfeasible. Even so, the representation of that dental model to the average dentition can still be contested. In this study, we attempted to create a more clinically relevant artefact, while maintaining an ISO10360-part 4 (1994) assessment test. The use of seven spheres placed at different heights and distributed evenly antero-posteriorly, instead of a single sphere as dictated by the ISO standard, will assist in identifying spatial accuracy of multiple elements in-relevance to each other, similar to multiple adjacent teeth. Furthermore, the dimensions of the horseshoe shaped SSM were chosen to resemble the dental arch in such a way that the SSM would fit a medium-sized impression stock-tray with a 2 mm clearance from tray walls for impression material, as would a dental arch in a clinical setting.

Albeit the incise™ possesses superior scanning properties, in-regards to accuracy and precision, yet, other factors of scanning should also be considered when using the stylus profilometer to scan tooth wear on stone-fabricated dental casts. The exhaustive scan of the stylus profilometer requires more than double the scanning time, with up to two hours for one dental cast, versus 30-45 minutes when using the laser scanner. Furthermore, the presence of undercuts or acute angled scanned surfaces might interfere with the scanning stylus ball-end and prevent it from appropriately contacting and fully scanning that surface, hence, potentially limiting the spatial resolution in constricted landmarks. Given the smooth surface of the SSM, this limitation was not evident in the scans acquired and consequently the calculated accuracy and precision of the scanner.

It is also worth noting the FARO™ arm assessment results attained in this study complied with manufacturers' stated accuracy of 80μm, which further supports the validity of the 3D scanner assessment methodology developed and employed in this study.

Other aspects of 3D scanning that need considering when comparing both 3D scanners is the operator training required. Scanning using the incise™ requires minimal operator training and the scanning procedure is fully automated, while operating the FARO™ scanner requires more training and is more technique-sensitive.

The use of intra-oral scanners would eliminate any potential errors arising from impression making, cast pouring and setting expansion. Currently there are more than ten intra-oral scanning systems, all aimed at overcoming the aforementioned disadvantages, improving patient dental experience and streamlining dental workflow (Logozzo et al., 2013). However, intra-oral scanners present a number of challenges that need to be considered with regards to the impact of micro-geometry, reflectivity, inclination of surface and inaccessible undercuts on the acquired scan data (Wieland et al., 2001). Furthermore, a consensus over a widely- accepted calibration and validation methodology to determine the accuracy and precision of intra-oral scanners remains lacking (Van der Meer et al., 2012). This would explain the varying, and sometimes conflicting, results demonstrated by different studies investigating the accuracy and precision of intra-oral scanners. Van der Meer et al. used a reference model resembling the dimensions of the dental arch, similar to this study, with three precision cylinders placed in a tripod formation, to assess the accuracy of three intra-oral scanners, CEREC (Sirona), iTero (Cadent) and Lava COS (3M) (Van der Meer et al., 2012). The distances between the three cylinders on the reference model were identified using an ultra-precision contact scanner with a precision of 0.1 µm (Leitz PMM 12106) then compared to those measured on scans acquired by the intra-oral scanners. Results demonstrated that the Lava COS had the highest accuracy with an accuracy range between 14.6µm ±12.7µm and 23.5µm ±14.2, followed by the iTero with an accuracy range of 61.1µm ±53.9µm and 70.5µm ±56.3µm and CEREC with an accuracy range of 79.6µm ±77.1µm and 81.6µm ±52.5µm. Güth et al. compared the accuracy and precision of direct scanning, indirect scanning of polyether impressions and indirect scanning of stone casts *in-vitro* (Güth et al., 2012). A titanium model representing a premolar and molar, with a chamfer preparation for a four-unit bridge and scanned using an industrial computerised tomography (CT) system, was used as a reference model. The reference model was: lightly powdered using Lava scan-powder then directly scanned using the Lava C.O.S intra-oral scanner; polyether impressions were taken of the reference model and scanned using a CT system; impressions were poured into casts and then scanned using a laboratory scanner, Lava Scan ST. Results demonstrated that direct scanning accomplished the most accurate results (17µm/-13µm; StDev ±19µm), followed by impression scanning (23µm/-22µm; StDev ±31µm) and cast scanning (36µm/-35µm; StDev ±52µm). Another study compared direct scans of a reference model using Cerec AC Bluecam and the Lava COS system intra-oral scanners to indirect scanning and demonstrated a precision was 61.3 +/- 17.9µm for conventional impression with polyether, 30.9 +/- 7.1µm for the Cerec Bluecam and 60.1 +/- 31.3µm for the Lava COS (Ender and Mehl, 2010). On the other hand, Flügge et al. scanned one patient's maxillary and mandibular arches 10 times using the iTero intra-oral scanner and compared the scans with extra-oral ones acquired through scanning polyether impression-poured casts of patient's dentition scanned using the iTero intra-oral scanner and the D-250 laboratory indirect scanner. Direct intra-oral scanning achieved the least precision (mean deviation 50µm, median deviation 37µm); followed by iTero scanning of casts (mean deviation 25µm, median deviation 18µm) and D-250 scanning of casts (mean deviation 10µm, median deviation 5µm). The authors concluded that direct scanning was less accurate than indirect scanning and attributed it to the presence of saliva and limited scanning space. These findings are in agreement with those attained by Ender and Mehl in a study comparing direct scans of a reference model using CEREC AC system intra-oral scanner and indirect scans of stone cast replicas of the reference model (Ender and Mehl, 2013a). The study concluded that direct scanning was significantly less accurate ($p<.001$) than indirect scanning.

Any 3D scan will only be as accurate as the surface it is scanning. Monitoring the progression of tooth wear in patients requires the taking of dental impressions of patients' teeth and then pouring them in dental stone, to fabricate a dental cast that will then be 3D scanned. Ergo, the fabricated cast needs to be an accurate representation of the patient's dentition. Moreover this procedure needs to be repeated at fixed intervals of time, with scan comparisons carried out annually or bi-annually. Hence, the use of an impression material that can accurately replicate dentition fine details, followed by the use of a low-expansion stone to pour the dental impression becomes essential. The standardisation of the impression material and dental stone used is also cardinal to avoid the introduction of any dimensional stability changes, through material expansion and/or shrinkage, caused by the use of different materials.

ANSI/ADA specification 19 addresses the accuracy of dental stone through the reproduction of a 0.02mm line grooved on a calibrated model of a flat steel disk with a 30mm diameter. However, given the ANSI/ADA calibration model's dimensions, the test has limited clinical significance (Quick et al., 1992, Shah et al., 2004). Similar studies have attempted to assess the dimensional accuracy of impression materials using 3D scanning technology, though some did not employ the use of a calibrated model (Imbery et al., 2010, Shah et al., 2004). Others have used manual callipers to calibrate their models (Caputi and Varvara, 2008), however the 2-dimensional nature of this method has inherent limitations. Additionally, when intra-oral scanners have been used, the application of a reflective powder on the scanned surface was required (Guth et al., 2013). The use of such a reflective powder has the potential to produce inconsistent layers and therefore adversely affect the accuracy and precision of the scan (Ender and Mehl, 2013b). On the other hand, a systematic review concluded that dimensional discrepancies between conventional stone casts and digital models remain clinically acceptable (Tarawneh et al., 2008).

In this study, alginate fabricated casts demonstrated the largest discrepancy, producing undersized casts of -35µm ±64µm difference compared to SSM. Polyvinylsiloxane produced the most accurate of casts with 12µm ±34µm oversized casts but concurrently demonstrated greater statistical variance when compared to polyether (25µm ±29µm). Hilmi et al. in a recent study compared the accuracy of polyvinylsiloxanes and polyether impressions by taking 30 impressions of a prepared molar and premolar that were poured then their mesio-distal and bucco-lingual dimensions measured using digital callipers (Hilmi et al., 2013). The study demonstrated comparable accuracy measurements to our study, with polyether accuracy ranging between -12µm to 95µm while polyvinylsiloxane had an accuracy range between –6µm and 126µm, when compared to the reference model. Similar dimensional differences have also been reported by other studies (Persson et al., 2008, Imbery et al., 2010, Rodriguez and Bartlett, 2011, Steinhauser-Andresen et al., 2011).

The Type IV stone (high strength, low expansion) used in this study exhibited continued expansion between 0.2%- 1.4% of volume at one month, corresponding to a linear expansion of 27µm ±20µm, which was of statistical significance, when compared to the initial 24-hour measurements. A similar study supports the aforementioned findings and reports delayed Type IV stone expansion of 0.35% at 120 hours (Heshmati et al., 2002). In contrast, ADA specification 25 states that Type IV stone should exhibit a maximum setting expansion of 0.1% at 2-hours post-pouring. However, it seems that such casts continue exhibiting dimensional changes beyond 2 hours post-pouring. It is also worth noting that a number of tooth wear studies have used epoxy die resin as the material of choice for the fabrication of dental casts later analysed for tooth wear progression (Pintado et al., 1997, Khan et al., 1999, Larsen et al., 2000, Schlueter et al., 2005). However, a study comparing the linear dimensional accuracy of 7 die materials, using a Unitron Microscope Model DMM 200, concluded that epoxy resin die materials demonstrated shrinkage comparable to the expansion of the Types IV and V dies, with shrinkage ranging between -0.1% to 0.3% (Kenyon et al., 2005). This further highlights the disparity in methodologies employed for monitoring tooth wear and consequently the challenges in comparing the wear rates attained by different studies. Hence, it is cardinal to establish a standardised approach to measuring tooth wear where each stage of the process is appropriately assessed and accounted for as part of the overall scanning system performance.

There was a necessity to formulate a customised 3D analysis protocol employing commercially available software, which was in this study Geomagic Qualify™. This necessity arises from two main factors: the scarcity of research literature addressing the issue of 3D dental analysis and the use of industrially geared software that has not been developed for dental applications. Hence, special attention was given to ensure that both Best-fit registration and 3D deviation analysis stage were accurate and their results are a true representative of changes occurring clinically. As a result, a number of measures were employed to minimise possible errors and discrepancies that might potentially skew the 3D analysis results. These measures are divided into two stages: pre-scanning analysis and intra-scanning analysis. The pre-scanning analysis stage consisted of calibration of the 3D scanning system and identification of dimensional accuracy and dimensional stability of dental stone casts at various potential scanning times, initial visual inspection of impressions made of patients' dentition, the use of Type IV dental stone (low-expansion, high strength), the use of vacuum mixing and vibration during stone casting and visual inspection of resultant dental casts. The next stage consisted of: initial inspection of the 3D scanned surface and elimination of any obvious errors/ discrepancies on scan surface, removal of the soft-tissue area surrounding the scanned teeth, the use of an exhaustive 1500 point-iteration during Best-fit registration and repeating it for 3 times, Best-fit registration of teeth on an individual-basis and the incorporation of a safety analysis margin of 140µm to account for unidentified errors arising from impression taking, stone casting and 3D scanning stages.

A number of studies have used similar methodologies to clinically quantify the progression of tooth wear *in*-vivo over time. Chadwick et al. formulated their own methodology for quantifying tooth wear through taking polyvinylsiloxane impressions of the dentition at different epochs, then brush coating the surface of the impressions with a high silver content electro-conductive paint. Once the paint dries, a further coat of cyanoacrylate-based gel was applied to further reinforce the paint. Thereafter, impressions were poured using die-stone to produce an electro-conductive replica covered with silver paint. The electro-conductive replicas were then scanned using a custom-made mapping device consisting of a precision X, Y and Z table motorised by the addition of two computer-controlled stepper motors that controlled the position of the table in the x, y planes. A third stepper motor governed the position of an electrical probe relative to the replica being scanned. The scanning method produced a data terrain map consisting of numerous X, Y and Z coordinates. Data terrain maps of replicas from different epochs where then compared through a custom formulated surface matching process/algorithm where the sum of squares of the surface separations (x, y and z coordinates of both terrain maps) were minimised (Mitchell and Chadwick, 1998, Mitchell and Chadwick, 1999). The authors estimated that the methodology had a precision of 15µm with an ability to detect tooth wear at 50µm (Mitchell et al., 2003) and demonstrating that the interpolation error of surface positions, during comparisons of surface terrain data maps, constitutes a '*surprisingly*' large proportion of the system error (Mitchell et al., 2004). However, the methodology has a number of limitations. The process of producing electro-conductive replicas is an added stage that is not part of routine laboratory practice requiring the allocation of extra resources. The scanner remains a research tool that is not commercially available. The surface-matching process experienced a number of anomalous incidents preventing the procedure from being fully automated, necessitating human intervention (Mitchell et al., 2003). The initial methodology yielded considerable amount of tooth wear data that was rated by clinicians as being difficult to interpret (Chadwick and Mitchell, 1999) and allowing only semi-quantitative analyses to be carried out (Schlueter et al., 2005). However, further refinement of the methodology was carried out and employed to quantify erosion in 251 school children (Chadwick et al., 2005).

Rodriguez et al. used an industrial non-contacting laser scanner (Xyris 2000TL - Taicaan®, Southampton, UK) to quantify tooth wear *in-vivo* (Rodriguez et al., 2012a). Prior to that, the authors assessed the accuracy and repeatability/precision of their non-contact laser profilometer (NCLP) using a four-step assessment approach: length assessment, volume assessment, dental assessment of step-height and volume changes, and accuracy assessment of scan-superimposition (Rodriguez et al., 2012b). For length assessment, the authors used an industrial gauge block measuring 25 mm × 35 mm × 9 mm (Part No: 611635-131, Mitutoyo® Corporation – Japan, Japanese Industrial Standard number B7506, 1997), where the block was scanned five times using the NCLP then analysed the scans using Geomagic™ Qualify 11. Differences between the NCLP acquired scans and the calibrated gauge block demonstrated a maximum mean error of 1.3 µm. For volume assessment, a volumetric standard was built with four custom-made titanium frusturns (cones) of increasing volume that were individually weighted to identify their true volume. Full details and dimensions of the volumetric standard were not available in published study. The frusturns also had to be carbon coated to avoid reflectivity issues with laser scanning. Thereafter, the frusturns were scanned five times using the NCLP and resultant scans volume-analysed using Geomagic™ Qualify 11. Volume assessment demonstrated differences ranging between 1.7% volume difference between frustrum true volume and scans, for the frusturn weighing 0.0409g, and 11.7% for the frusturn weighing 0.0176g, with scan volume error increasing with decrease in volume of scanned frustrum. To assess dental step-height and volume changes, the authors used a customised maxillary phantom-head dental model. Cuspal inclinations of teeth were prepared on selected teeth to simulate tooth wear. Laboratory silicone was used to take an impression of the prepared model, and then poured using Type IV dental stone. Thereafter, engineering slip gages of known height and titanium occlusal onlys and palatal veneers of known volume were custom fabricated and cemented onto the surfaces of the prepared teeth, on the stone model, using cyanoacrylate glue. The previously acquired laboratory silicone impression was re-poured in stone, representing the dentition post-tooth wear, while the originally-poured model, with the cemented slip gages, onlays and veneers, represented the baseline state of the dentition prior to tooth wear. Both casts were scanned using the NCLP. Both models were scanned, best-fit registered and 3D deviation analysed using Geomagic™ Qualify 11. Interestingly, in-order to quantify the cement space between the onlays and the cast, a contact scanner had to employed (Cyclone®, Renishaw®, Wotton-under-edge, UK). Results demonstrated a volume difference of up to 46%, which was attributed to the shadow created on the cervical portion of one of the onlays by the laser spot creating an undercut, '*a well-recognised disadvantage of optical scanners*' as noted by the authors.

Moreover, Rodriguez et al. proceeded to assess the accuracy of the scan superimposition through taking five maxillary impressions, of one of the authors, using heavy and light-bodied putty silicone impression, then pouring the impressions in dental stone. One of the resultant casts was randomly selected and scanned five times using the NCLP, with the scan images superimposed. To assess the repeatability of the impression technique, the remaining casts were scanned once and compared. Results demonstrated that repeated superimpositions of the same-cast scans had an accuracy of 2.7µm (StDev 2.8µm), while casts from different impression-takings demonstrated a median difference ranging between 2 – 3.6µm.

In another study, Rodriguez and Bartlett attempted to assess the dimensional stability of polyvinylsiloxanes and polyethers (Rodriguez and Bartlett, 2011). To do so, the authors used the ADA specification no. 19 block and a custom 50 mm by 50 mm square block with multiple features (grooves and peaks). Impressions were taken of both blocks and scanned using the NCLP. The blocks were also scanned directly using the NCLP. Differences between the direct scan and stone cast scans were analysed using Boddies v1.81 surface metrology software (Taicaan® Technologies, Southampton, UK). Results for the custom block demonstrated a general trend towards impression materials contracting when compared to the directly scanned surface of the custom block but this was less clear when compared with data from the ADA block. All impressions also expanded over the 12-week time interval. Bar the Aquasil® DECA and Take 1®, none of the other impression materials of the ADA block and the custom block were statistically significant different in measurements on the 'X' axis for the ADA block, or for any of the axes for the custom block, over 12 weeks ($p > 0.05$). All materials showed linear changes within the allowed limits recommended by the American Dental Association (<1.5%).

There seem to be several parallels between this study and those carried out by Rodriguez et al. The aim of both studies is to quantify tooth wear *in-vivo* using 3D scanners and mainly employed the same 3D matching software (Geomagic™ Qualify 11), in the absence of reference points and through the employment of best-fit registration techniques. Both studies have attempted to assess the accuracy and repeatability/precision of the 3D scanners using calibrated models with known 'true measurements' as a comparison reference against 3D scanner acquired images of the calibrated models. Both studies have also assessed the dimensional stability of different impression materials over time as an important parameter in monitoring the progression of tooth wear using 3D scanning technology over time. It is worth noting though that our study protocol was submitted in March 2010, with ethical approval attained in December 2010, prior to publication of any of Rodriguez et al. studies. Hence, duplication of study protocols or methodologies was not possible.

However, there are also distinct differences between the studies. Rodriguez et al. employed a non-contact laser scanner in their studies. The authors also undertook an exhaustive approach towards assessment of their NCLP and software superimposition, through assessing length and volume of calibrated reference and dental models, of which their relevance can be debatable. Moreover, Rodriguez and Bartlett assessed dimensional stability of impression materials through directly scanning the impressions, rather than pouring the impression in stone, hence, eliminating any potential errors that might be introduced through the casting process or stone induced dimensional changes.

On the other hand, the employment of six different assessment methods (Mitutoyo® gauge block; frusturns; metal engineering slip gages, onlays and veneers; stone casts of author's dentition; ADA block and custom block) complicates the methodology, preclude others from repeating the experiments, especially in the absence of detailed description of testing methods, and flags the issue of clinical relevance of some of the assessment methods employed. Furthermore, the use of two 3D matching software programs (Geomagic™ Qualify 11 and Boddies v1.81), with two different algorithms, can induce unwarranted errors and inconsistencies during superimposition of images. Moreover, Rodriguez et al.

did not assess the dimensional accuracy and dimensional stability of stone casts poured from different impression materials. However, in their clinical study, aimed at monitoring the progression of tooth wear in patients, the authors did not directly scan the dental impression, instead, the authors poured the impressions in Type IV dental stone then scanned the resultant stone casts using the NCLP (Rodriguez et al., 2012a). Hence, an important factor, the dimensional accuracy and stability of dental casts, was not accounted for in the study's results of *in-vivo* measurements of tooth wear in patients over 12 months.

The findings of this study highlight the importance of using a standardised scanning protocol of dental casts, given the demonstrated material and time dependent dimensional changes exhibited by the casts, if accurate comparisons and reliable resultant measurements are to be attained. This is of particular relevance to studies that require highly accurate and truly representative measurements, such as tooth wear studies.

4.2 Clinical findings

The aims of the initial clinical survey study were to provide a descriptive investigation of a patient cohort referred by GDPs to a secondary care setting for management of tooth wear and determine outcomes of the patient referral pathway. The overall patient return rate of the survey was 67%, which compares favourably to similar studies (Donachie and Walls, 1995, Bartlett et al., 2005). Limited consultation time and patients not attending on the day of consultation contributed towards the varying return rates.

Thirty-five percent of GDP patient referral letters examined in this study did not record any underlying aetiological causes for the observed tooth wear. Furthermore, 98% of referrals did not include diagnostic study casts that might potentially assist in identifying tooth wear progression over a given time period and presenting the receiving specialist with a baseline comparison.

The findings of this study demonstrate that referred tooth wear patients within this Scottish sub population were more likely to be young to middle-aged males inhabiting socio-economically deprived areas who were concerned by their tooth wear condition for which aesthetics was their main reason for concern. These findings are comparable to other studies investigating different geographical populations where males predominated GDP tooth wear referrals, aesthetics was the primary presenting complaint and socio-economic deprivation and age were directly associated with tooth wear (Smith et al., 1997, Al-Omiri et al., 2006, Van't Spijker et al., 2009, Wazani et al., 2012).

An understanding of the demographics and needs of tooth wear patients will assist in delivering the appropriate care that these patients require and seek. Furthermore, identifying the various factors associated with tooth wear, such as bruxism, aesthetic concerns and socio-economic deprivation, will help towards diagnosing and managing other underlying disorders that might be concomitant with tooth wear, such as stress, depression, eating disorders, alcohol and drug dependencies (Ahmed, 2013). Indeed, in this study we identified a predominance of patients originating from lower socio-economic groupings within the tooth wear referral cohort. This is of particular relevance to the population involved in this study as Glasgow suffers from a 30% increased rate of premature deaths compared to cities of similar socio-economic deprivation distribution in the UK and more than half the excess deaths occurring in males under the age of 65 are directly related to alcohol and drugs (Walsh et al., 2010).

Referral to secondary-care can be considered as part of the overall-management process of tooth wear, through provision of a treatment plan or specialist clinical management of severe/advanced tooth wear cases. Interestingly, 92% of referred tooth wear patients were identified as not requiring clinical specialist treatment. These findings tend to raise questions in regards to the extent of tooth wear management in primary care. Furthermore, the lack of mention of a diagnosed aetiological cause and lack of inclusion of study casts of the patient's dentition at an earlier time point might divest reviewing consultants of valuable diagnostic data. These findings imply a need for increased awareness amongst primary dental care providers in regards to management of tooth wear, which can be provided through continued professional development.

In order to further improve secondary care provision for tooth wear patients, a more specific tooth wear referral system needs to be implemented. This referral system needs to ensure the inclusion of the diagnosed, underlying aetiological factor(s) of the observed tooth wear and the patient's principal reason of concern contributing towards the referral. Furthermore, the referral letter should also mention any previous tooth wear management attempts carried out by the referring GDP, such as dietary advice, splint therapy, oral hygiene advice and/or composite build-ups. Dental casts taken previously can be sent with the referral letter or presented by the patient on the day of consultation, as this would present a baseline comparison to the patient's current dentition.

The findings of the patient questionnaire do indicate the presence of multiple tooth wear risk factors in all patients. However, attrition risk factors (grinding, clenching, nail and pencil biting) were the common denominator present in all the patients. This is further supported by the earlier findings of the survey that demonstrated that attrition was diagnosed as the primary aetiological cause of tooth wear in the majority of patients referred to GDH&S by GDPs for management of tooth wear. Moreover, the 3D analysis demonstrated that although all patients demonstrated tooth wear of over 140µm, however, the area affected by tooth wear was limited, with a median surface area of tooth wear being 2% (n=120). Furthermore, in the eleven patients examined in this study, 53% of teeth included (n=64/120) presented with 0.1% - 2% of surface area affected by tooth wear. The clinical understanding of attrition would indicate a restricted, yet repeated, effect on the surface of teeth involved in the para-functional habit, corresponding with the limited median surface area of tooth wear demonstrated in this study. This is in contrast to the expected wider wear pattern affecting the surface of teeth due to acidic dissolution or toothbrush abrasion encountered clinically. On the other hand, it would be clinically very difficult to confirm that the detected tooth wear was solely as a result of attrition, and that other factors, such as erosion, did not contribute to its progression, based on patient self-reporting.

At one year recall there was a high dropout rate (63%, *n*= 11/30). Participants were sent two appointments via letters sent by mail, in-line with GDH&S appointment booking policy. If participants still did not attend their second appointment; they were contacted via telephone by the main investigator. This dropout rate can be explained in the fact that these patients were previously screened by a restorative consultant and advised that their tooth wear did not require restorative intervention due to its limited or slow progression and hence were either returned to their GDP or placed on the hypnotherapy waiting list; a waiting list which was at the time of the study extending to over nine months prior to first appointment. Furthermore, there were no incentives for patients to attend their appointments or continue participating in the study. It was explained that this is an experimental pilot study and that the participants would not be reimbursed for their time or effort. Consequently, given the research and ethics committee recommendations, data acquired from participants who dropout from the study could not be included or analysed. Rodriguez et al. experienced a high dropout rate (52%) similar to our study which the authors attributed to patients' and referring practitioners' decision that present tooth wear was limited or inactive with no consequence to longevity of present dentition (Rodriguez et al., 2012a). Another reason stated by the authors was the need for repeated visits by the patients to Guy's Hospital and the associated travel time and inconvenience. It is also worth noting that the original intent of the clinical stage of this study was to monitor the progression of tooth wear in patients over a two–year period. However, due to the high dropout rate and other logistical limitations, in-regards to availability of clinical space and support, a pragmatic decision was made to conclude data-collection at one-year.

The use of polyether (PE) as the material of choice for *in-vivo* impression-taking of patients' dentition was based on the high-accuracy and consistency of resultant poured stone casts scanned 1 month post-pouring (accuracy: 25µm; precision: ±29µm), in-comparison to the higher-accuracy yet greater variability exhibited by polyvinylsiloxane

(PVS) poured casts (12µm ±34µm), as demonstrated in this study. However, the choice of impression material should not be based solely on accuracy, but also on other factors, such as hydrophobicity of PVS versus the hydrophilicity of PE, which is an important clinically-relevant factor for accurate surface replication and successful impression taking (Rubel, 2007).

The process of 3D sectioning the teeth and individually best-fit registering them using Geomagic software has been previously carried-out by Tarawneh et al. in a study aimed at comparing the occlusal surface characteristics of dental casts fabricated from alginate and polyvinylsiloxane impressions through scanning the casts with a computed tomography scanner (FlashCT®) possessing a reported accuracy of ±50µm and resolution of 127µm (Tarawneh et al., 2008). The authors tested the repeatability/reproducibility of the sectioning and best-fit registration process of 113 teeth. Study results demonstrated that the volume difference of repeated 3D analysis/repeated superimposition was not statistically significant at -0.032mm^3 (StDev ±0.48).

Al-Omiri et al., attempted to quantify the progression of anterior tooth wear in 50 undergraduate dental students experiencing tooth wear over a period of one year (Al-Omiri et al., 2013). Participants' degree of tooth wear was clinically assessed using the Smith and Knight index, thereafter irreversible hydrocolloid impressions were taken of the patients' dentition at baseline and after one year and poured using Type III dental stone. The anterior teeth on the resultant casts were sectioned interdentally forming individual dies that were then scanned using the Laser Cercon System (Cercon Smart Ceramics, Germany). Resultant scan images were printed and examined using a toolmaker microscope (Stedall-Dowding Machine Tool Company, Optique et Mecanique de Precision, Marcel Aubert SA, Switzerland). Finally, the dental dies were directly measured using the toolmaker microscope. The study demonstrated that direct measurement of the casts using the toolmaker microscope was capable of detecting greater values of tooth wear, compared to the Cercon scanner. Tooth wear detected using the toolmaker microscope demonstrated mean tooth wear of 130µm ±20µm for 300 anterior teeth at one year. Furthermore, when using the Smith and Knight index, examined teeth yielded similar results, with minimal changes to scores, at baseline and one year later demonstrating the absence of visually detectable tooth wear. Al-Omiri et al. had previously used the same methodology to monitor tooth wear progression in 20 undergraduate dental students over a period of 6 months (Al-Omiri et al., 2010). Results demonstrated mean tooth wear of 582 µm (StDev 50µm) when using the tool makers microscope and mean tooth wear of 165 µm (StDev 27µm) when using the CAD/CAM laser scanner, with none of the participants scoring 3 or 4 (advanced wear) on the Smith and Knight index.

Al-Omiri et al studies used irreversible hydrocolloids for impression taking and Type III gypsum for pouring of impressions. Irreversible hydrcolloid impressions possess inferior accuracy and demonstrate greater discrepancies, when compared to elastomeric impression materials (Chen et al., 2004, Peutzfeldt and Asmussen, 1989). Furthermore, the studies do not mention the time of scan acquirement, whether it was carried-out immediately post-pouring or at a later stage. Such information is important given the documented expansion of Type III dental stone of 0.2%, which is twice that of Type IV dental stone (ISO standard specification ISO 6873:2013; ANSI/ADA specification No.25). This setting expansion undoubtedly will affect the accuracy of any attained measurements through cast scanning. Further complicating matters is the fact that the authors did not carry out any independent assessment of the accuracy and precision of the scanners used in their studies. Moreover, in both studies, participants were all undergraduate dental students; hence, their true representation of the tooth wear population may be questionable.

In a similar study, Rodriguez et al. monitored the progression of tooth wear in 63 patients over a period of 12 months (Rodriguez et al., 2012a). Patients were given a questionnaire, highlighting dietary, para-functional and gastric risk factors, to complete. Thereafter, polyvinylsiloxane impressions were taken of their dentition at baseline, six months and at 12 months. Impressions were poured using Type IV dental stone then scanned using the previously discussed NCLP (Xyris 2000TL - Taicaan®, Southampton, UK) with 3D analysis carried out using Geomagic® Qualify 11. The methodology used for 3D analysis consisted of trimming the full arch scans, transformation of image into a CAD format, then full-arch Best-fit registration was carried-out through the random selection of 300 data points on the scans (as an alignment reference), followed by further fine-alignment using 1000 points. To measure tooth wear, the authors created a digital mesh of measuring points, separated one mm on the X, Y and Z axis, and laid over the superimposed scan surfaces. All positive values measured on the superimposed scans (denoting growth) were then set to a value of zero, since '*surface growth is not possible'*, as stated by authors. At twelve months patient recall, the study's dropout rate was 52% (*n*= 33/63). Results of the study demonstrated that, out of 521 teeth scanned at twelve months, only 11 teeth (seven anterior teeth and four posteriors) experienced tooth wear greater than 100 µm, whilst the remaining teeth presented with wear that was less than the previously calculated scanning uncertainty/error of the system, 15µm. The most commonly affected teeth were the upper anterior teeth and upper and lower molars, with the greatest median wear present at the upper central incisors and lower molars. As for dietary, para-functional and gastric risk factors, data analysis was not possible at 12 months due to small sample size (n= 30). However, at six months (n= 63) univariate regression analysis demonstrated that regurgitation symptoms and vomiting were the only risk factors significantly associated with progression of tooth wear. Finally, the authors concluded that result comparisons with other studies should be made with caution, given the varying methodologies employed in different studies. Furthermore, Rodriguez et al. demonstrated that upper central incisors were the most commonly affected teeth with greatest wear values at 12 months. Similarly, in our pilot study, the 3D analysis of the 130 teeth (11 patients) monitored for 12 months demonstrated that upper central incisors were the largest tooth group affected by Grade 3 depth of tooth wear (380 - >500µm) and possessing the greatest mean total surface area of detected tooth wear amongst all tooth groups, with mean tooth wear surface area of 6.1% (StDev: ±5%). Hence, the findings of Rodriguez et al. and the findings of our pilot study support the use of teeth-specific partial recording for monitoring tooth wear progression. These specific teeth can act as markers or indicators for the rate of progression of tooth wear in patients. Additionally, regarding statistical analysis, Rodriguez et al. decided that given the novel methodology employed in their study, with no previous data present, power calculations were not possible.

On the other hand, Rodriguez et al. did not measure the dimensional stability of the Type IV dental stone used for impression pouring, nor was the time of cast scanning mentioned, similarly to Al-Omiri et al.'s study. Dental stone expansion introduces a variable that needs to be accounted for when scanning stone casts poured at different time-intervals. The time of cast scanning remains unclear and raises doubts regarding the accuracy of the acquired, then superimposed, scans of casts poured at different time-intervals. Furthermore, the authors superimposed full-arch images. As a result, if an error was present on one or multiple teeth, this error might affect the over-all superimposition of scans, and possibly magnify errors present in the positive and negative values of the best-fit registration. Moreover, while the authors mention the depth of measured tooth wear, yet it seems that the employed methodology could not map-out the surface area distribution of the measured tooth wear, as this was not mentioned in the findings, nor were there any figures clearly denoting examples of patient or tooth specific wear measurements using the newly developed methodology. The ability of producing a surface map of measured tooth wear is a valuable tool for relating tooth wear to aetiology, such as incisal tooth wear to bruxism, as well as a potentially important mean for patient education and raising awareness.

In this pilot study, we were able to formulate a novel descriptive methodology capable of assessing the accuracy and precision of contact and non-contact 3D scanners. We also assessed the dimensional accuracy of Type IV stone casts poured from different impression materials and identified the casts' dimensional stability over time and consequently defined the overall performance of the 3D scanning system. Furthermore, we translated our *in-vitro* methodology and successfully applied it *in-vivo,* through monitoring the progression of tooth wear in patients over a period of twelve months, and consequently producing accurate and detailed quantification data of tooth wear as well as a colour-coded map demonstrating the depth and surface area of the detected tooth wear. To do so, we had to develop a software methodology with several safety measures to ensure accurate 3D analysis and true tooth wear measurements. The detailed calibration and assessment carried out in this pilot study of each of the individual stages of the 3D scanning, dentition reproduction (impression taking and cast pouring) and 3D analysis can present a comprehensive reference for future studies to compare their findings against and can offer an opportunity to develop a standardised protocol for monitoring the rate of tooth wear progression *in-vivo*. Moreover, the multi-stage and detailed assessment approach employed in this pilot study assists other researchers and clinicians in identifying the expected overall 3D scanning system performance when using different impression materials and/or when scanning the resultant casts at different time frames, hence standardising tooth wear progression monitoring. Once a standardised and accurate tooth wear monitoring protocol has been established, clinical challenges that are currently present can be overcome, such as: establishing clear thresholds that distinguish physiological from pathological tooth wear and determining evidence-based clinical management recommendations.

Inevitably, this study also has its limitations. The methodology of determining the overall performance of the 3D scanning system is exhaustive. While the data collected in this study, in regards to the dimensional accuracy and dimensional stability of Type IV stone casts poured from different impression materials and scanned at different time intervals, can be used as a reference for others to account for those scanning variables, yet determining the 3D scanner's accuracy and precision remains a necessity when using alternative 3D scanners to those assessed in this study. Furthermore, we have demonstrated the limitations of use of contact profilometery, especially in-reference to scanning time, however, scanning is not the only time consuming process. Preparing the acquired 3D scans, trimming the soft-tissue area, individually Best-fitting teeth, carrying out the 3D deviation analysis, exporting the resultant data and analysing it - while all of these stages ensure accuracy of attained measurements, yet the process remains an arduous one requiring the procurement of specialised software and operator training, in-addition to the time required to carry out the actual 3D analysis process. As a result, the use of the methodology would be very challenging if used to measure full dental arch tooth wear in very large cohorts of patients or wide-scale epidemiological studies. The data generated alone would be overwhelming. However, further development of the software analysis through formulation of a simplified, user-friendly, interface, in-addition to increased operator experience will ensure a definitive improvement in the 3D analysis time. Moreover, the scanning and analysis of specific teeth (central incisors, canines and molars) and employing them as key indictors of tooth wear progression, as demonstrated in this study and others, will assist in expediting the process. Finally, the presence of a 24-months tooth wear data would have benefited this study through offering an extra data-set to compare against baseline and 12-months tooth wear data-sets. This data–set could have assisted in further refining the 3D analysis process and the DSPI.

5. Developed index: The Dental Surface Profiling Index (DSPI)

The DSPI is capable of quantifying tooth wear at a threshold of 140μm. This threshold is based on a establishing a safety of measurement margin that ensures that the detected tooth wear is a true representation of the clinical progression of tooth wear, rather than an error arising from impression taking and pouring and/or 3D scanning and analysis error. The data is presented in two forms: tabulated percentage distribution of tooth surface area affected by varying depths of tooth wear, and a colour-coded map demonstrating depth and surface area of tooth wear, denoted by different colours.

3D analysis data of *in-vivo* progression of tooth wear over a period of 12 months, acquired from the 11 study participants (130 teeth), was collected, tabulated, analysed and utilised to form the basis for the proposed index.

The Geomagic™ generated 3D analysis reports utilised a graded scale of 40μm to demonstrate distribution of depth of tooth wear. This 40μm increment was selected as it approximates the previously calculated overall system performance of the methodology employed in this study. The generated 3D analysis report tabulated depth in 12 groups (20 – 60μm, 60 – 100μm, 100 – 140μm, 140 – 180μm, 180 – 220μm, 220 – 260μm, etc.) (Table 5.1). In this study, the system performance ($\boldsymbol{\alpha}_{\mathbf{system}}$) for scanning one object was around 33μm for each acquired scan. However, when superimposing and comparing two scans of two objects, each with its own scanning uncertainty/error, the relative overall system performance ($\boldsymbol{\alpha}_{\mathbf{relative}}$) becomes 33μm **x** 2= 66μm. This 66μm system performance reflects the absolute accuracy of the system under ideal conditions of scanning, replication and analysis of a simple geometrical object, the SSM. However, as previously mentioned, if we take into account other potential errors occurring in a clinical setting, under less than ideal conditions, and arising from impression taking, cast pouring, scanning, 3D analysis of patient's dentition with its complex anatomy, and then attempting to use the 66μm would seem challenging. Hence, a safety threshold margin of 140μm was selected, that was twice the relative overall 3D scanning system performance, for monitoring the depth progression of tooth wear using the DSPI (Table 5.2). As a result, for tooth wear depth, only 6 groups of depth were used in each 3D analysis report, starting from 140 – 180μm to 380 - >500 μm. To simplify grouping and indexing of results, depth groups were consolidated into three grades based on a 120µm depth-progression of detected tooth wear; Grade 1: 140 – 260 µm, Grade 2: 260 – 380 µm and Grade 3: 380 - >500 µm.

For tooth wear surface area distribution, the detected distribution of tooth wear in the study-participants' teeth was: sixty-eight percent demonstrated tooth wear surface area of 0.1% - 4% (*n*= 82/120), eighteen percent (*n*= 22/120) demonstrated >4 – 8% and thirteen percent (*n*= 16/120) demonstrated >8% of tooth wear surface area. Hence, to simplify classification of tooth wear surface area distribution for clinical application of the index, a three tier classification was proposed that consisted of: Class A: 0- 4%, Class B: 4- 8% and Class C: ≥8%.

Finally, there was a need to indicate a threshold distinguishing localised from generalised tooth wear. Hence, localised tooth wear was defined as: a dentition presenting with tooth wear progression affecting ≤ 30% of scanned teeth and demonstrating a detected depth of wear of Grade 1 or more (≥140 µm). Generalised tooth wear was defined as a dentition presenting with tooth wear progression affecting >30% of scanned teeth and demonstrating a detected depth of wear of Grade 1 or more (≥140 µm). This distribution of generalised and localised tooth wear is based on the Basic Periodontal Examination and employs a similar protocol in-relevance to the Basic Erosive Wear Evaluation.

One of the important features of the DSPI is its ability to, not only to detect depth of tooth wear, but also to outline and quantify the percentage of tooth surface area affected by wear. This feature would assist in identifying and associating the underlying tooth wear aetiology to a specific form/behaviour of detected tooth wear over time. It could also further support present clinical knowledge of aetiology-specific patterns of wear with accurate 3D analysis data. An example of this would be the presence of incisal tooth wear caused by attrition due to nail biting (Figure 5.1), combination of intrinsic erosion and attrition affecting the incisal and palatal surface of teeth (Figure 5.2), or the effect of tooth brushing on the cervico-buccal surface of teeth (Figure 5.3).

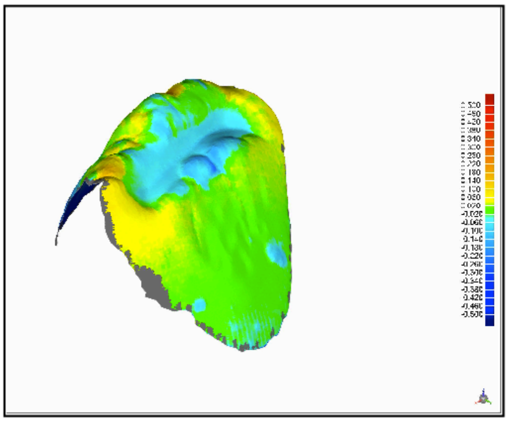
Table 5.1: Example of a 3D deviation analysis report generated by Geomagic Qualify™ and comparing scans of a single tooth initially (reference) and after one year (test). Report demonstrates distribution of dimensional changes (Deviation Distribution) in the form of a table, a histogram and a colour-coded map. The colour-coded map is at 40µm increment scale (20µm to -20µm (green), -20µm to -60µm, -60µm to -100µm, etc.).

3D Comparison Results

Reference Model	[redacted]
Test Model	[redacted]
No. of Data Points	19301
# Outliers	138

Tolerance Type	3D Deviation
Units	mm
Max. Critical	0.500
Max. Nominal	0.020
Min. Nominal	-0.020
Min. Critical	-0.500

Deviation	
Max. Upper Deviation	0.446
Max. Lower Deviation	-0.470
Average Deviation	0.033 / -0.086
Standard Deviation	0.103



Deviation Distribution

>=Min	<Max	# Points	%
-0.500	-0.460	12	0.062
-0.460	-0.420	139	0.720
-0.420	-0.380	156	0.808
-0.380	-0.340	194	1.005
-0.340	-0.300	245	1.269
-0.300	-0.260	407	2.109
-0.260	-0.220	362	1.876
-0.220	-0.180	412	2.135
-0.180	-0.140	400	2.072
-0.140	-0.100	561	2.907
-0.100	-0.060	1775	9.196
-0.060	-0.020	2513	13.020
-0.020	0.020	7322	37.936
0.020	0.060	3989	20.667
0.060	0.100	452	2.342
0.100	0.140	176	0.912
0.140	0.180	83	0.430
0.180	0.220	42	0.218
0.220	0.260	24	0.124
0.260	0.300	11	0.057
0.300	0.340	10	0.052
0.340	0.380	3	0.016
0.380	0.420	9	0.047
0.420	0.460	4	0.021
0.460	0.500	0	0.000

Out of Upper Critical	0	0.000
Out of Lower Critical	0	0.000

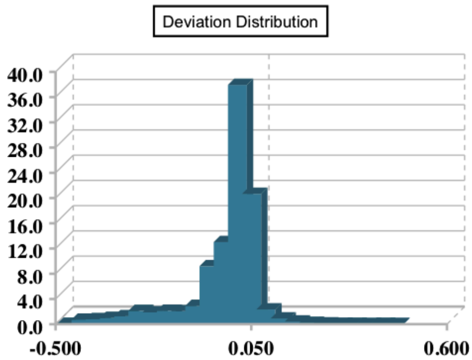
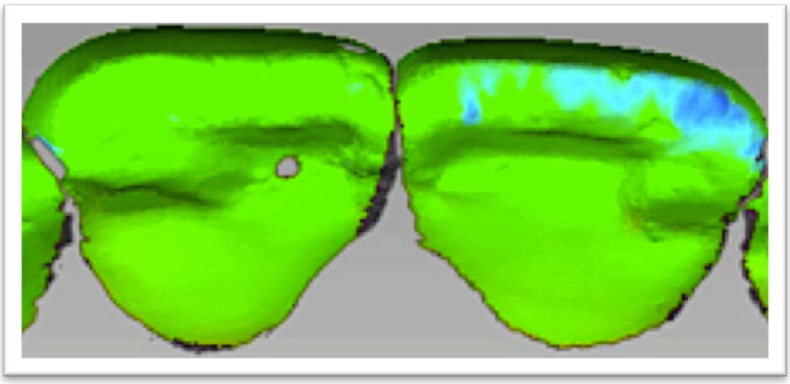


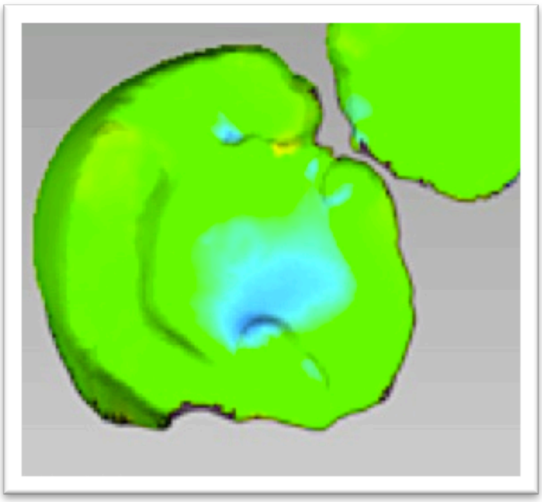
Table 5.2: The Dental Surface Profiling Index (DSPI).

The Dental Surface Profiling Index (DSPI)	
Depth of tooth wear	
Grade 1	140 - 260µm
Grade 2	260 - 380µm
Grade 3	380 - ≥500µm
Surface Area of tooth wear	
Class A	0 - 4% of tooth surface
Class B	4- 8% of tooth surface
Class C	>8% of tooth surface
Distribution of tooth wear	
Localised	≤30% of teeth with ≥ Grade 1 depth of wear
Generalised	>30% of teeth with ≥ Grade 1 depth of wear



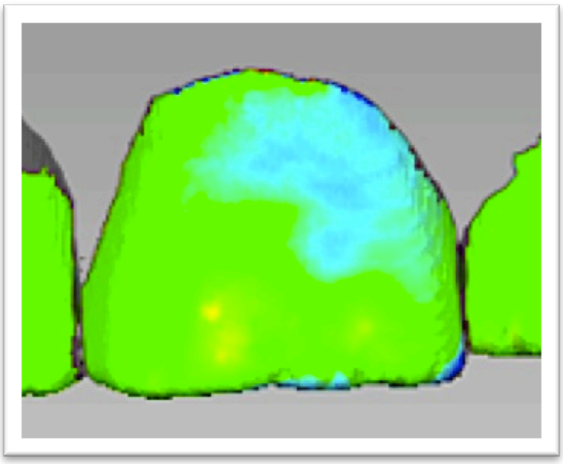
Tooth	D 21
Age	26
Gender	Male
History	Attrition (grinding+ nail biting)
Depth and surface area of tooth wear	
Grade 1	4.2%
Grade 2	4.1%
Grade 3	0.1%

Figure 5.1: 3D colour coded mapping of tooth wear progression demonstrating the surface area and depth of tooth wear caused by attrition.



Tooth	I 13
Age	55
Gender	Male
History	Attrition (clenching)+ Intrinsic Erosion
Depth and surface area of tooth wear	
Grade 1	7.7%
Grade 2	0.7%
Grade 3	0.2%

Figure 5.2: 3D colour coded mapping of tooth wear progression demonstrating the surface area and depth of tooth wear caused by a combination of attrition and intrinsic erosion.



Tooth	F 11
Age	50
Gender	Male
History	Abrasion (horizontal brushing +whitening toothpaste), Attrition (grinding+ nail biting)
Depth and surface area of tooth wear	
Grade 1	11%
Grade 2	1%
Grade 3	0%

Figure 5.3: 3D colour coded mapping of tooth wear progression demonstrating the surface area and depth of tooth wear caused by a combination of abrasion and attrition.

Advantages of DSPI

The Dental Surface Profiling Index (DSPI) addresses a number of challenges that present in managing tooth wear using currently available tooth wear indices. The most obvious challenge being the high subjectivity in quantifying and monitoring tooth wear in patients. However, managing tooth wear is not limited to mere restorative intervention; tooth wear management also requires raising patient awareness and understanding of their tooth wear condition. This management approach will ensure future patient co-operation and compliance. Yet, clinician-patient communication can also be challenging in-regards to attempting to relay multifaceted clinical findings and complex treatment needs, as well as justification of potential management modalities, and expressing them in layman simple terms.

Hence, DSPI offers a number of advantages that address the aforementioned challenges:

- Accurate, objective and reliable identification of dental dimensional changes over time, including tooth wear
- Detailed report generation quantifying both depth and distribution of dental dimensional changes
- Index is based on a standardised, calibrated and repeatable methodology
- Employs 3D dental scanners developed for CAD/CAM dental applications, given that scanner interface allows export and open access to resultant scans
- Does not require customised software algorithms but rather employs commercially available 3D matching software and uses available software options
- Ease of clinician-patient communication of findings. Results are presented visually in the form of a colour-coded scan map, which can aid clinicians in patient management and interpretation of findings, hence, potentially improving patients' compliance, in-addition to the detailed analysis report. This method of presentation was demonstrated by others to be an excellent way to present wear results to clinicians for clinical application (Chadwick and Mitchell, 1999).

Disadvantages of DSPI

The DSPI possesses a number of limitations. These limitations in-essence relate to three main aspects: training, logistics and time. There is a need for operator training on scanner use as well as software analysis procedure. Logistically, the procurement of specialised 3D scanners and 3D analysis software can present another challenge in the use of the DSPI. However, in this study, we were capable of employing a contact 3D scanner that is commercially used for CAD/CAM scanning and fabrication of indirect restorations and is readily available. Geomagic Qualify™, albeit not formulated for dental application, however is also readily available. Finally, time is potentially the most important disadvantage facing wide scale clinical use of DSPI. While scanning time, which might take up to two hours for a full-arch scan, is completely automated when using *incise*™ scanner. However, 3D scan-analysis, in this study, required approximately 30 minutes for completion of analysis of 12 anterior teeth. While a reduction in analysis time is expected with gained operator experience, yet, the procedure of 3D scanning and analysis remains time consuming and might challenge the use of the DSPI in clinical trials involving large cohorts of patients or epidemiological studies. Hence, DSPI, at present, can be considered as a research tool/aid rather than a routine clinically applied index.

Hence, the disadvantages of the DSPI can be summed as:

- Requires operator training. Training time might differ based on individual needs
- Requires procurement of a 3D scanning equipment, that allows open export of scan data, and 3D matching software. A potential financial burden if sole purpose of use is to quantify tooth wear
- Analysis can be time consuming
- If alternative scanning systems are used, appropriate calibration is needed to identify overall system performance. However, impression materials and dental stone assessment data presented in this study can be used as a reference.

6. Case reports

The following case reports are examples of different types of tooth wear detected through 3D scanning analysis of study participants' dentition over a period of 12 months.

The study participants were recruited as previously discussed in the 'Ethics and participant recruitment' section. The participants did not require restorative intervention, however, they were either referred to hypnotherapy and/or their tooth wear placed under-observation and monitored using study models. This tooth wear management decision was deemed appropriate by the initial screening restorative dentistry consultant/s at GDH&S.

Study participants were asked to complete a history questionnaire covering their medical and dental history, lifestyle factors, habits and diet. Polyether impressions were taken of their dentition initially, as previously outlined in the 'Impression taking, cast-pouring and cast-scanning' section. The maxillary and mandibular anterior teeth on the resultant casts were scanned one-month post-pouring using the *incise*™ 3D contact scanner.

Participants were recalled at one year post their initial impression-taking appointment. Their medical and dental history was reviewed and any changes were noted. At the time of the recall, none of the participants presented with any changes to their medical history and none of the participants noted any dental interventions in the past year. Thereafter, the impression taking, cast pouring and cast scanning procedure was repeated in the same manner as initial visit.

Initial (T^O) and recall (T^1) scans of participants' anterior teeth were imported to Geomagic Qualify™. Each tooth present in the T^1 scan was Best-fit registered to its counterpart on the T^O scan then 3D deviation analysis was carried-out. Dimensional differences between the scans were identified and a detailed analysis report generated.

To simplify analysis and results presentation, dimensional changes were grouped into three grades, based on depth of tooth wear. Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm.

6.1 Case report 1: localised tooth wear

Patient 'C' is a 56 y/o female (Figure 3.4 – 3.6)

Positive findings from history questionnaire:

- Aware of condition for >10 years
- Depression
- Insomnia
- Dry eyes
- Antidepressants
- Fruit juices: everyday, 4 – 7 glasses
- Fruit consumption: 15 – 35 portions/week
- Grinding – grinding sounds
- Clenching
- Jaw pain started 6 – 9 years ago
- Jaw stiffness in the morning
- Neck pain and discomfort

3D analysis of tooth wear at one year (Table 6.1 and Figures 6.1 – 6.6):

- Generalised minimal or no tooth wear (≤ Grade 1)
- Localised areas of Grade 2 and 3 depth of tooth wear present on 4-7% of palatal and incisal surfaces of Upper Central Incisors

Diagnosis:

Based on positive history findings and 3D analysis of tooth wear over a period of one year, patient presents with localised areas of tooth wear affecting upper central incisors of Grade 2-3 tooth wear depth present on 4-7% of palatal and incisal surfaces of affected teeth. Findings support the diagnosis of attrition as the main aetiology of tooth wear caused by active bruxing para-functional habit and triggered by depression.

Figure 6.1: Labial view of patient 'C' anterior teeth

Figure 6.2: Occlusal view of patient 'C' maxillary anterior teeth

Figure 6.3: Occlusal view of patient 'C' mandibular anterior teeth

Table 6.1: Depth and surface area of tooth wear detected in 12 anterior teeth over a period of one year for patient 'C' and using the 3D scanning system threshold of 140 microns. Results grouped in 3 grades based on depth of tooth wear: Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm. FDI tooth numbering used.

Tooth	Grade 1	Grade 2	Grade 3	Total
C 13	1.0%	0.6%	0.1%	1.7%
C 12	0.6%	0.5%	0.1%	1.2%
C 11	3.7%	2.5%	0.9%	7.1%
C 21	2.4%	1.3%	0.6%	4.3%
C 22	0.4%	0.1%	0.0%	0.5%
C 23	0.5%	0.0%	0.0%	0.5%
C 33	0.4%	0.3%	0.1%	0.7%
C 32	0.0%	0.0%	0.0%	0.0%
C 31	0.5%	0.1%	0.0%	0.6%
C 41	0.1%	0.0%	0.0%	0.1%
C 42	0.5%	0.0%	0.0%	0.5%
C 43	0.0%	0.0%	0.0%	0.0%

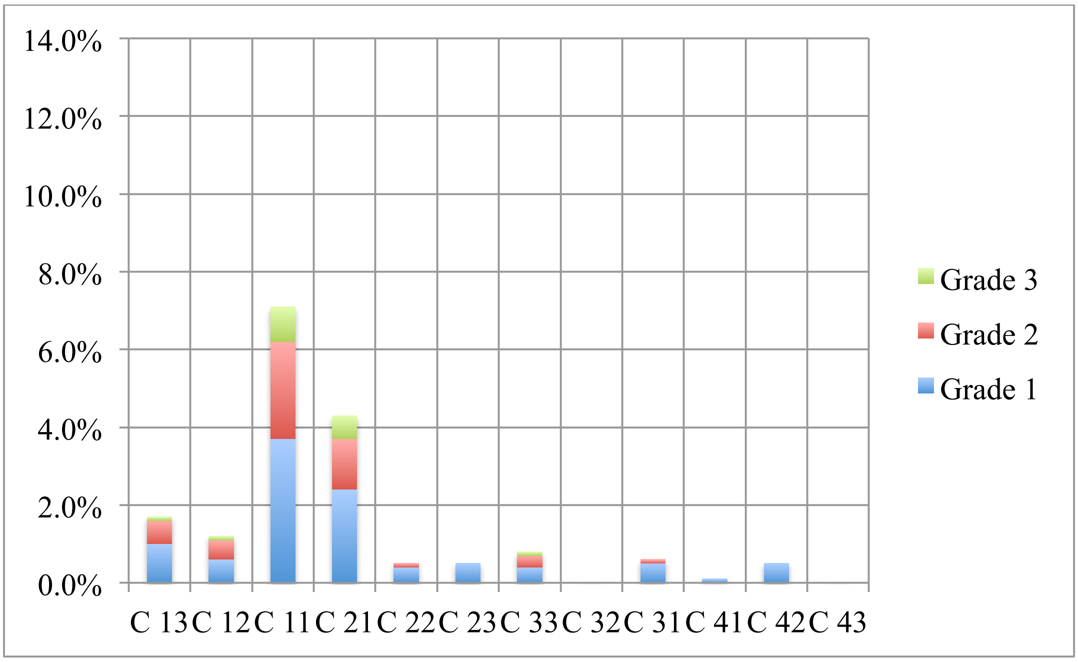


Figure 6.4: Depth and surface area of tooth wear detected in 12 anterior teeth over a period of one year for patient 'C' and using the 3D scanning system threshold of 140 microns. Results grouped in 3 grades based on depth of tooth wear. Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm. FDI tooth numbering used.

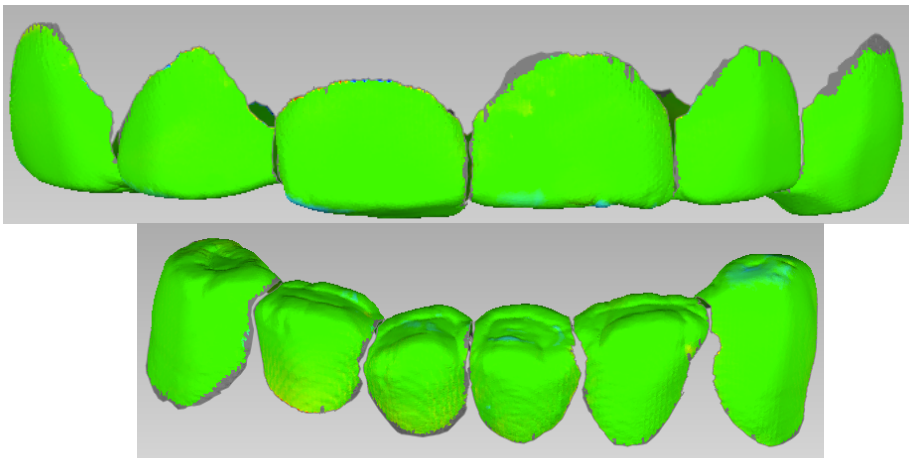


Figure 6.5: 3D deviation analysis colour-coded map demonstrating labial view of patient 'C' anterior maxially and mandibular teeth.

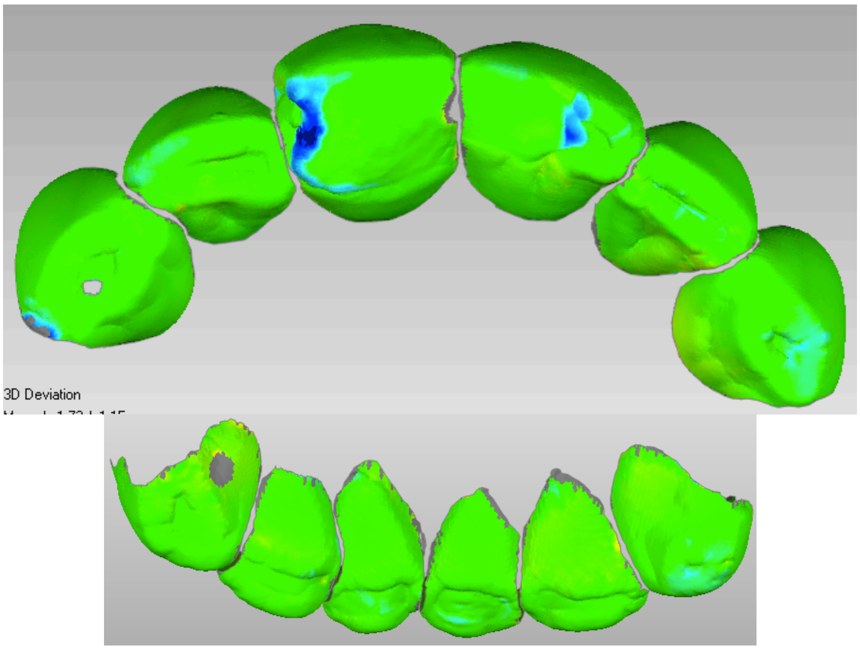
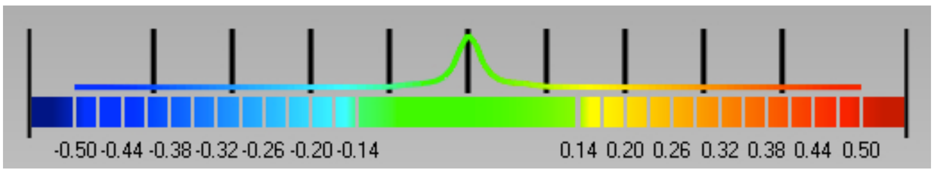


Figure 6.6: 3D deviation analysis colour-coded map demonstrating occlusal view of patient 'C' anterior maxillary and mandibular teeth demonstrating localised tooth wear on incisal and palatal surfaces of anteriors.



6.2 Case report 2: generalised tooth wear

Patient ‘B’ is a 46 y/o male (Figures 3.10 – 3.12)

Positive findings from history questionnaire:

- Aware of condition for 1 – 5 years
- Extremely stressful lifestyle (10/10)
- Clenching
- Grinding

3D analysis of tooth wear at one year (Table 6.2 and Figures 6.7 – 6.12):

- Generalised (≥ 30) tooth wear of Grade 2 and 3
- Localised areas of Grade 2 and 3 depth of tooth wear present on 2-12 % of buccal, incisal and palatal surfaces of all teeth, with Upper Right Central Incisor presenting with greatest surface area of tooth wear (12%) and Lower Left Canine presenting with greatest depth (Grade 3, 10% surface area)

Diagnosis:

Based on positive history findings and 3D analysis of tooth wear over a period of one year, patient presents with generalised tooth wear, with Upper Right Central Incisor and Lower Left Canine demonstrating pronounced depth and distribution of tooth wear. These findings support the diagnosis of attrition as the main aetiology of tooth wear caused by active bruxing para-functional habit triggered by stress. However, 3D analysis results of cervico-buccal surfaces of upper anterior teeth also suggest an active role of abrasion, potentially due to inappropriate tooth brushing/ dentifrice use, especially on Upper Central Incisors.

Figure 6.7: Labial view of patient 'B' anterior teeth

Figure 6.8: Occlusal view of patient 'B' maxillary anterior teeth

Figure 6.9: Occlusal view of patient 'B' mandibular anterior teeth

Table 6.2: Depth and surface area of tooth wear detected in 12 anterior teeth over a period of one year for patient 'B' and using the 3D scanning system threshold of 140 microns. Results grouped in 3 grades based on depth of tooth wear: Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm. FDI tooth numbering used.

Tooth	Grade 1	Grade 2	Grade 3	Total
B 13	1.0%	0.5%	0.5%	2.0%
B 12	4.1%	2.8%	0.0%	6.9%
B 11	6.1%	4.4%	1.6%	12.1%
B 21	5.0%	1.6%	0.7%	7.3%
B 22	2.0%	0.0%	0.0%	2.0%
B 23	2.1%	0.5%	0.0%	2.7%
B 33	3.7%	3.2%	2.7%	9.6%
B 32	0.4%	1.1%	0.0%	1.5%
B 31	2.7%	0.2%	0.0%	2.8%
B 41	0.2%	0.3%	0.0%	0.5%
B 42	2.5%	0.2%	0.0%	2.7%
B 43	1.1%	0.8%	0.2%	2.2%

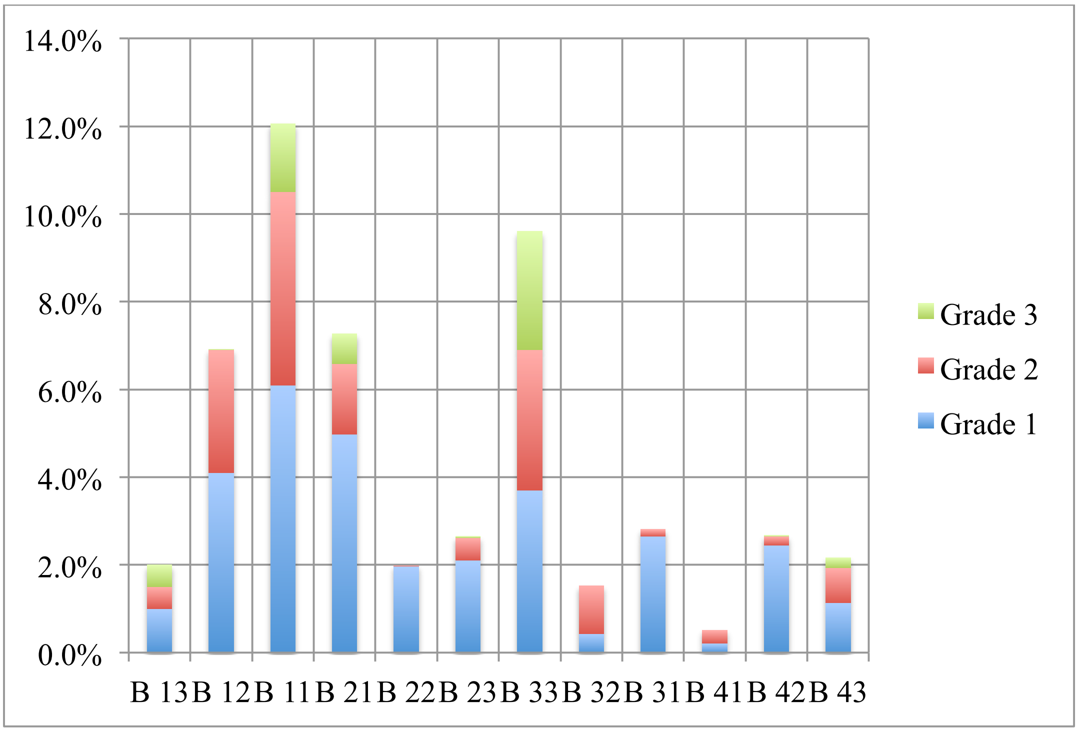


Figure 6.10: Depth and surface area of tooth wear detected in 12 anterior teeth over a period of one year for patient 'B' and using the 3D scanning system threshold of 140 microns. Results grouped in 3 grades based on depth of tooth wear. Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm. FDI tooth numbering used.

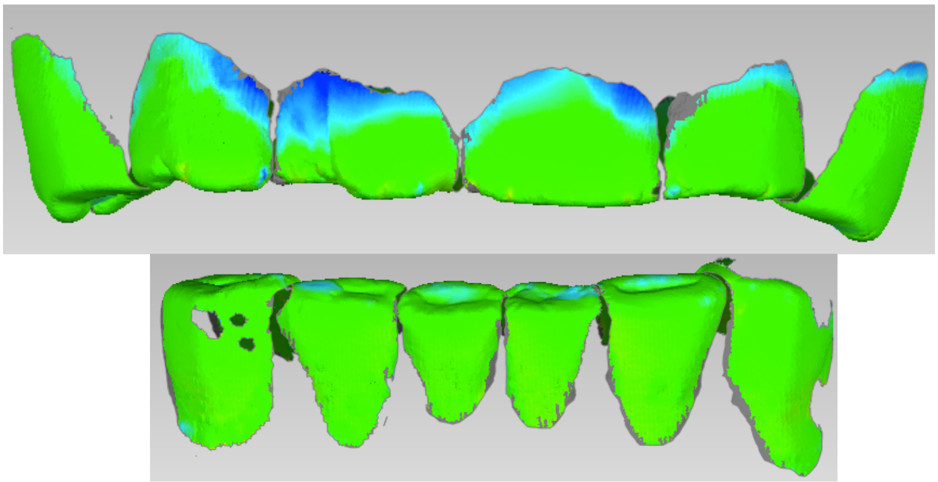


Figure 6.11: 3D deviation analysis colour-coded map demonstrating labial view of patient 'B' anterior maxillary and mandibular teeth. Generalised tooth wear present cervically and incisally on all anteriors, denoted in blue.

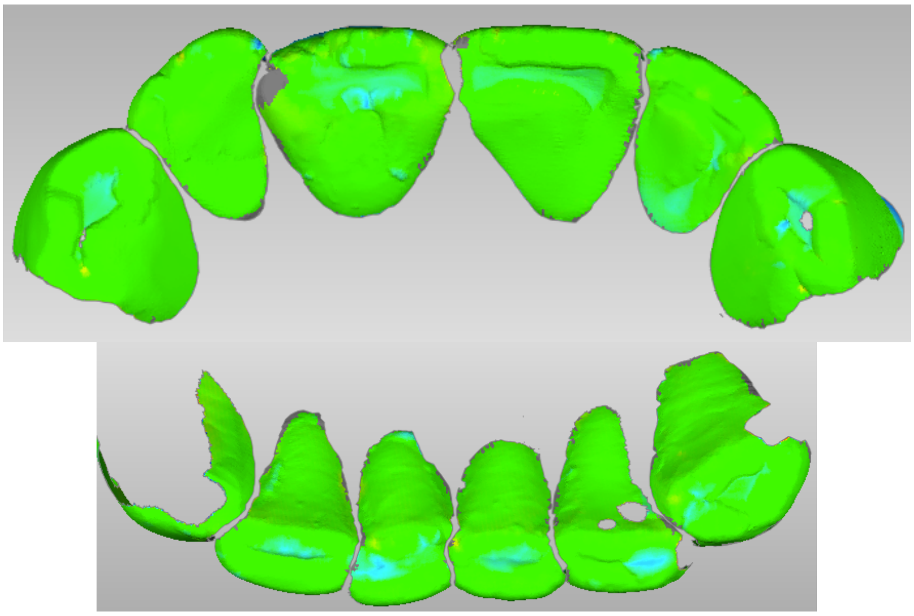
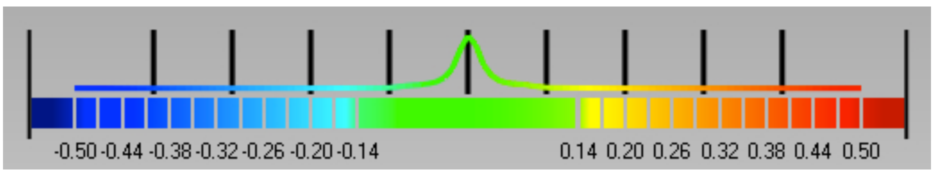


Figure 6.12: 3D deviation analysis colour-coded map demonstrating occlusal view of patient 'B' anterior maxillary and mandibular teeth. Generalised tooth wear present on incisal and palatal surfaces of most teeth, denoted in blue.



6.3 Case report 3: Early/minimal or no tooth wear

Patient 'J' is a 28 y/o male. Due to archiving errors outwith the investigators' control, patient 'J's intra-oral pictures were not accessible.

Positive findings from history questionnaire:

- Aware of condition for 1-5yrs
- GORD, Frequent heart burn, headaches
- Omeparazole, pain killers
- Stressful lifestyle (7-9/10)
- Nail/pencil biting
- Grinding
- Clenching
- Jaw pain/discomfort, clicking for <1yr

3D analysis of tooth wear at one year (Table 6.3 and Figures 6.13– 6.15):

- Generalised minimal or no tooth wear (≤ Grade 1)
- Localised areas of minimal distribution of tooth wear (1- 2%) affecting Upper Right Canine, Upper Central Incisors and Lower Left Central Incisor.

Diagnosis:

Based on positive history findings and 3D analysis of tooth wear over a period of one year, patient presents with minimal or no tooth wear. However, presence of frequent heartburn episodes, GORD and grinding/clenching, coupled with a progressive increase in teeth surface areas affected by tooth wear, as denoted by 3D analysis, might indicate early stages of active intrinsic erosion and attrition.

Table 6.3: Depth and surface area of tooth wear detected in 12 anterior teeth over a period of one year for patient 'J' and using the 3D scanning system threshold of 140 microns. Results grouped in 3 grades based on depth of tooth wear. Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm. FDI tooth numbering used.

Tooth	Grade 1	Grade 2	Grade 3	Total
J 13	0.5%	0.4%	0.2%	1.1%
J 12	0.0%	0.0%	0.0%	0.1%
J 11	0.6%	0.3%	0.3%	1.2%
J 21	1.0%	0.2%	0.0%	1.3%
J 22	0.4%	0.1%	0.0%	0.5%
J 23	0.4%	0.3%	0.1%	0.7%
J 33	0.4%	0.2%	0.0%	0.6%
J 32	0.3%	0.0%	0.0%	0.3%
J 31	1.1%	0.6%	0.0%	1.7%
J 41	0.6%	0.1%	0.0%	0.7%
J 42	0.3%	0.2%	0.0%	0.5%
J 43	0.5%	0.2%	0.1%	0.8%

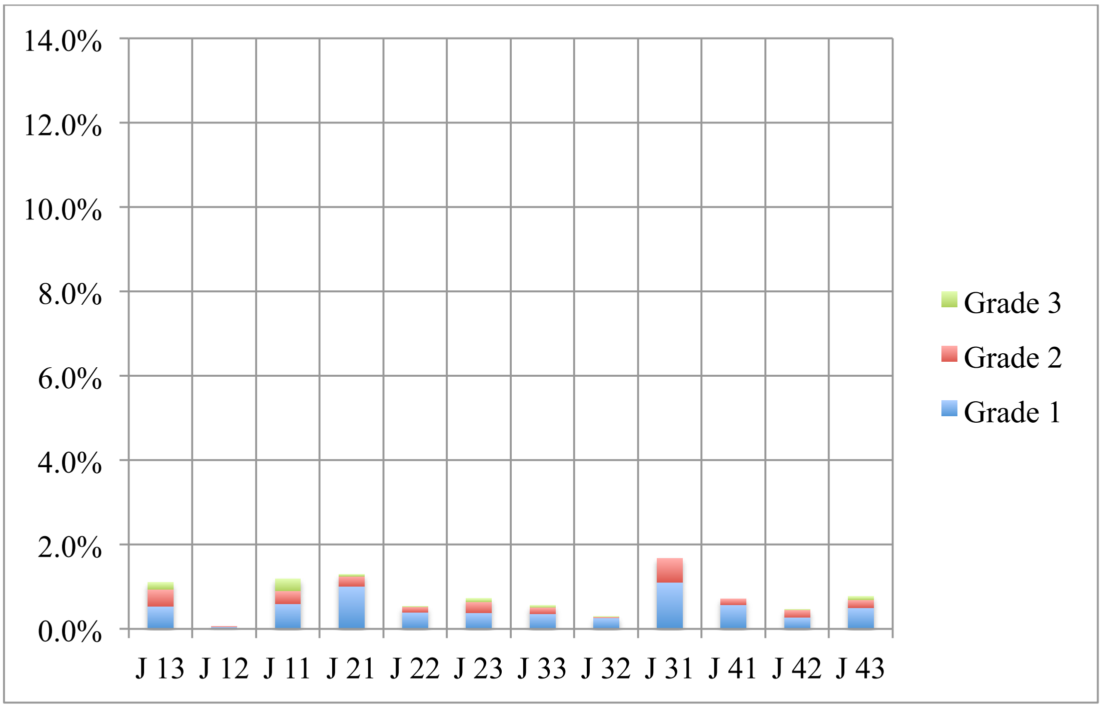


Figure 6.13: Depth and surface area of tooth wear detected in 12 anterior teeth over a period of one year for patient 'J' and using the 3D scanning system threshold of 140 microns. Results grouped in 3 grades based on depth of tooth wear. Grade 1: 140 – 260 µm; Grade 2: 260 – 380 µm; Grade 3: 380 - >500 µm. FDI tooth numbering used.

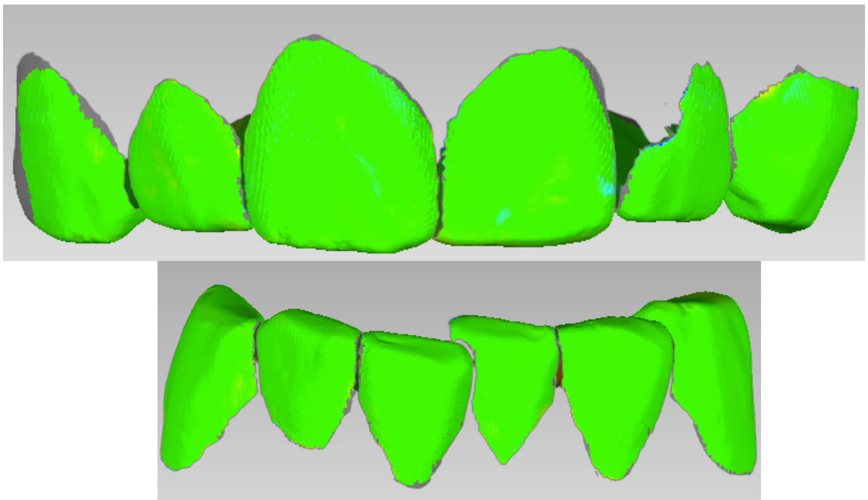


Figure 6.14: 3D deviation analysis colour-coded map demonstrating labial view of patient 'J' anterior maxillary and mandibular teeth. Minimal or no tooth wear detected.

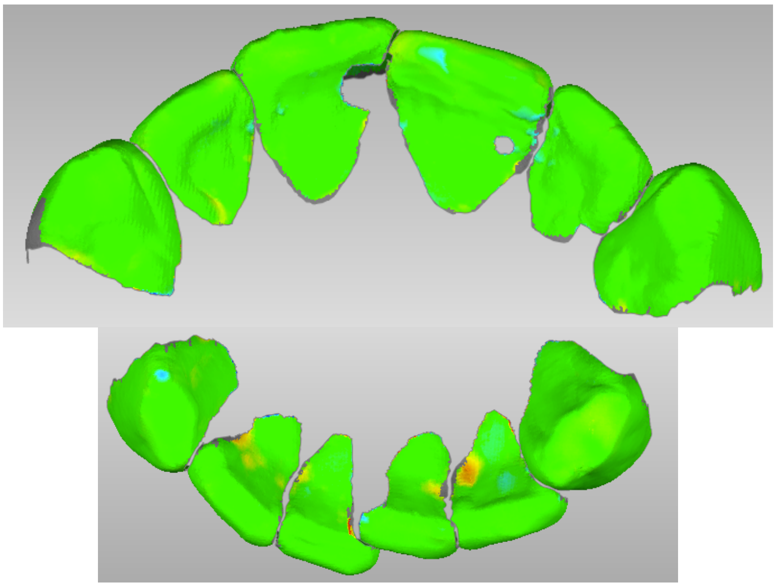
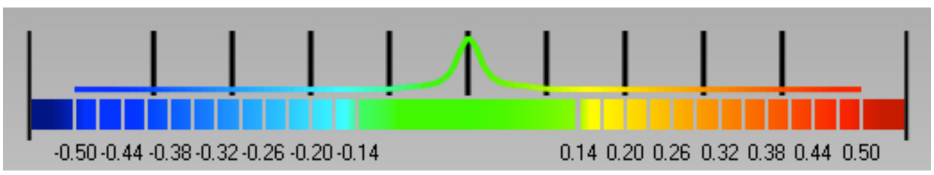


Figure 6.15: 3D deviation analysis colour-coded map demonstrating occlusal view of patient 'J' anterior maxillary and mandibular teeth. Early signs of tooth wear present on incisal edges of maxillary centrals and mandibular right canine. Dental stone blebs present in T^1 cast and translated to an increase in dimension on the lingual surface of mandibular incisors, denoted in yellow and red.



7. Conclusion

This chapter summarises the findings of this study, outlines the impact of those findings on current research and their contribution to existing literature and finally proposes future research protocols, based on the findings and limitations of this pilot study.

7.1 Summary of findings

The findings of this study are divided into two sections: calibration and assessment of the 3D scanning system, and the clinical application of the newly developed tooth wear assessment methodology and tooth wear survey findings.

- **Calibration and assessment of the 3D scanning system:**
  - The accuracy of the *incise*™ scanner was 2.8µm with a precision/repeatability of ±0.8µm (StDev), while the FARO™ scanner demonstrated an accuracy of 82µm with a precision/repeatability of ±40µm (StDev).
  - The mean dimensional accuracy of Type IV stone cast replicas of the stainless steel model (SSM) at 24-hours post-pouring was demonstrated to be -35µm ±64µm for Alginates, -25µm±29µm for polyethers and 12µm±34µm for polyvinylsiloxanes.
  - The mean dimensional stability of Type IV stone casts at 48-hours post-pouring was demonstrated to be 7µm ±27µm, when compared to 24-hours measurements of the SSM.
  - The mean dimensional stability of Type IV stone casts at 1-week post-pouring was demonstrated to be 15µm ±15µm, when compared to 24-hours measurements of the SSM. Measurement differences between 1-week and 24-hours measurements were significantly different (p=0.001).
  - The mean dimensional stability of Type IV stone casts at 1-month post-pouring was demonstrated to be 27µm ±20µm, when compared to 24-hours measurements of the SSM. Measurement differences between 1-month and 24-hours measurements were significantly different (p<0.001).
  - The overall 3D scanning system performance for polyether-poured casts scanned using the incise™ scanner at different time frames ranged from 28.5µm, when scanning casts at 24 hours post-pouring, to 35.8µm at 48 hours post-pouring. At one-month post-pouring, the overall 3D scanning system performance was determined to be 33µm. Consequently, the relative overall 3D scanning system performance when comparing two individual scans taken of casts poured from polyether impressions is: 33 **x** 2= 66µm.

- **Clinical application of the newly developed tooth wear assessment methodology and tooth wear survey findings:**
  - All patients (*n*=11) experienced either Grade 2 (260- 380µm) or Grade 3 (380 - >500µm) tooth wear depth, in one or more of their anterior teeth, over a period of 12 months, when ≥0.1% tooth wear affected surface area was considered.
  - 92% of all anterior teeth (*n*=120/130) demonstrated tooth wear of ≥140µm of depth over a period of one year. Within the anterior teeth presenting with tooth wear, 79% of those anterior teeth (*n*= 95/120) demonstrated ≥260 µm of tooth wear, presenting with either Grade 2 or Grade 3 tooth wear depth, and 31% (*n*= 37/120) demonstrated ≥ 380 µm, presenting as Grade 3 tooth wear depth.
  - The surface area affected by tooth wear in 53% of teeth (*n*=64/120) was ≤2%
  - Upper central incisors were the tooth group demonstrating the largest number of teeth presenting with Grade 3 tooth wear depth (32%, *n*= 12/37), followed by upper canines (30%, *n*=11/37).
  - Upper central incisors demonstrated the greatest mean total surface area of tooth wear (Grades1+2+3) amongst all tooth groups, with mean tooth wear distribution of 6.1% (StDev: ±5%).
  - A new tooth wear index that relies of 3D scanning data to quantify the progression of tooth wear *in-vivo* over time, using the newly developed methodology, was proposed. The Dental Surface Profiling Index (DSPI) classifies tooth wear according to depth (Grade 1: 140 – 260µm, Grade 2: 240-380µm and Grade 3: 380 - >500µm), surface area (Class A: <4%, Class B: 4-8% and Class C: >8%) and distribution (Localised: ≤30% of teeth and Generalised: >30% of teeth).
  - The tooth wear survey demonstrated that there was a statistically significant association between social deprivation and tooth wear in General Dental Practitioner (GDP) referrals to Glasgow Dental School and Hospital. Males aware of their tooth wear for the preceding 5 years presenting with appearance as their main complaint and displaying evidence of attrition were more likely to be referred by GDPs for specialist management or advice.

7.2 Impact of research

The methodology and findings of this study have managed to address a number of challenges, experienced by other tooth wear and 3D scanning studies, and have consequently proposed and applied solutions to these challenges. Therefore, we expect that this study will impact the formulation of future research protocols and methodologies in the field of 3D scanning technology, not only in-relevance to tooth wear studies, but expectantly in the wider scale of dental applications of 3D scanning.

The immediate impact of this study, within its limitations, can be summed as:

- Formulation of a calibration testing method that is clinically relevant to dentistry and capable of assessing the accuracy and precision of both contact and non-contact 3D scanners. This testing method has already been adopted by Renishaw Plc. as one of their internal testing methods for *incise*™ scanner assessment. The calibration testing method has also been utilised to ascertain the accuracy and precision of a novel scanner used in orthopaedic surgery (Joshi et al., 2013).

- The study's findings regarding the dimensional accuracy and dimensional stability of Type IV dental stone poured from different impression materials will have direct impact on dimensional assessment of stone casts measured at various time intervals. This is vital when direct measurements are taken of dental casts, such as in CAD/CAM of indirect restorations in restorative dentistry and orthodontic applications where linear measurements are required to assess tooth movement. While other studies have arrived to similar findings, yet in this study the employed systematic, calibrated and clinically relevant testing method demonstrated an impression material-specific accuracy for dental casts and monitors the dimensional accuracy changes of casts over a long period of time post-pouring, of up to one month.

- Clinically, the formulated tooth wear quantification method and proposed tooth wear index (DSPI), can be immediately employed by clinicians to routinely monitor tooth wear progression in patients over a period of time. This would assist in an accurate diagnosis of the underlying aetiology of the detected tooth wear. It would also assist clinicians in devising, customising or revaluating their tooth wear treatment plans. Furthermore, the currently proposed methodology would assist in identifying the success of various tooth wear management modalities and their effect on tooth wear progression. Finally, the methodology would also assist in monitoring patient compliance to treatment, with special relevance to those with underlying mental health disorders, such as eating disorders patients.

- Dental Biomaterial studies can also benefit from the proposed methodology, especially when monitoring the *in-vivo* wear of various restorative materials such as: composites, resin-modified glass ionomers, fissure sealants, ceramics, etc. This *in-vivo* wear monitoring would assist in identifying compatibility and wear resistance of these materials to applied occlussal forces, as-well as their contribution in tooth wear progression on opposing teeth.

- The clinical findings of this study's survey demonstrated a need for further development of the current tooth wear referral system at GDH&S in-addition to the need to increase awareness to current tooth wear management practices amongst primary care providers. These findings have been presented to the Clinical Governance Committee at GDH&S and new referral protocol is currently being devised.

7.3 Future research

The current study is a pilot study with its limitations of time, logistics and resources, however, it establishes fundamentals and presents a gateway for future research protocols and proposals aimed at further developing contemporary knowledge and understanding of tooth wear, its mechanisms of progression, underlying interaction of aetiology and efficacy of treatment planning.

Future research proposals would include:

- Identification of clear thresholds distinguishing physiological from pathological tooth wear. Ideally, larger cohorts of patients need to be recruited. Cohorts would need to be divided into two groups: experimental group comprising of participants diagnosed with active pathological tooth wear and a control group of participants deemed to have no pathological tooth wear. The values of tooth wear identified in this study would assist in establishing accurate power calculations and sample size determination in future studies.

- Further refinement of the proposed index (DSPI) re-evaluating the suitability of its 3D analysis threshold of 140µm through the employment of DSPI as means to clinically monitor tooth wear across a larger cohort of patients. A larger scale clinical study would also assist in further refinement of current distribution of depth and surface area grouping of 3D data.

- Randomised control studies aimed at identifying the efficacy of various treatment modalities in managing tooth wear in patients over time employing an accurate, objective and calibrated methodology resulting in findings that can be compared across-studies and deduce evidence-based recommendations for management.

- Development of DSPI into a treatment-needs based index, similar to the Community Periodontal Index for Treatment Needs (CPITN). The new tooth wear index would be able to assign patient treatment recommendations based on specific index scores /groups. Such an approach would standardise diagnosis, management and review of tooth wear. Furthermore, a treatment-recommendations based index would develop institution-based policies for streamlining referrals into secondary care through specifying specific scores for patients who require secondary care for their tooth wear condition.

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Appendices

Appendix 1: Tooth wear survey questionnaire.

<u>Section A</u>

Date of Birth: □ Gender: **Male**/**Female**

Postcode:

Referring practitioner: □ **GDP** □ **GMP** □ ***Other:***

Reasons for referral:

Aetiology specified: □ **Not specified** □ **Specified:**

Diagnostic models supplied: **Yes**/**No**

<u>Section B</u> *(to be completed by patient)*

- Patient aware of condition: **Yes**/**No**
- If 'Yes', how long has the patient been aware of the condition?

  □ **< 1** year □ **1 - 5** years □ **6 - 10** years □ **> 10** years

- If 'Yes', is the patient concerned about their condition?

  1 2 3 4 5 6 7 8 9 10

  1*: Not concerned* ***5****: Concerned* ***10****: Severely concerned*

- If 'Yes'; main reason for concern:

  □ **Aesthetics**
  □ **Sensitivity/Pain**
  □ **Function/Mastication**
  □**Speech**
  □ ***Other***, please specify:

<u>Section C</u> *(to be filled by clinician)*

- Clinician's diagnosis *(Aetiology)*:
- Referral outcome: □ **Undergraduate clinic** □ **Consultant clinic**

  □ **SHO** □ **SpR/SpT**

  □ **Hypnotherapy clinic** □ **Review**

  □ **Dentist with special interest** □ **Return to GDP**

  □ ***Other***, please specify:

Appendix 2: Patient Information Sheet

NHS Greater Glasgow and Clyde

University of Glasgow | Dental School

Patient Information Sheet

Short title: A Study of Tooth Wear (September 2010 v.1)

WHY HAVE I BEEN CHOSEN?

You are being invited to take part in this research study because you have been diagnosed with tooth wear. This requires monitoring of progression and possible treatment intervention. Please take time to read the following information carefully.

WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this study is to measure the amount of tooth wear in patients diagnosed with tooth wear using 3D scanning over a 2-year period. This will enable us to accurately monitor the progression of tooth wear and relate it to the underlying cause of the condition. Based on this information, accurate treatment decisions can be formulated. This study will form the basis for a PhD degree.

WHAT DO I HAVE TO DO? ARE THERE ANY RISKS?

Your participation involves attending Glasgow Dental Hospital and School (GDH&S) for a 30-minute appointment once every 6 months. On the first visit, you will be asked to complete a short questionnaire addressing dietary, habitual and medical aspects that might be causing your tooth wear. During the appointment impressions will be taken of your teeth. This is done using a duplicating material (impression material) placed in a tray and seated in your mouth to copy the shape and form of present teeth. This procedure will be carried out by an experienced clinician and is routinely done to monitor tooth wear. You may experience very minor discomfort caused by the presence of the impression tray in your mouth. This is immediately relieved once the tray is removed. <u>There are no additional clinical procedures associated with taking part in this study and the impressions are a normal part of monitoring and treating tooth wear.</u>

DO I HAVE TO TAKE PART?

It is up to you to decide whether or not to take part in this study and have impressions taken of your teeth. If you decide to take part in the study, you will be given this information sheet and consent form to sign and keep. You will have an opportunity to ask questions and have them answered to your satisfaction. If you choose not to take part in the study, you will not be disadvantaged in any way.

WHAT ARE THE BENEFITS OF MY TAKING PART?

By taking part in this study, you will be assisting us in monitoring the progression of tooth wear and relating it to underlying causes. The amount of tooth wear recorded by 3D scanning of a model of your teeth from the impression will be recorded in your case note at GDH&S. Such information might assist your treating clinician in deciding the need and type of dental treatment required for your tooth wear condition.

WHAT WILL HAPPEN TO MY SAMPLES AND PERSONAL DATA?

Your impressions and associated personal medical data and completed questionnaire ("Study Data") will be stored securely, processed and used for investigations within Glasgow Dental Hospital and School. All impressions will only be used for the purposes previously described.

The scanning of the dental model produced from your impressions, as well as the questionnaire, will provide information on monitored tooth wear for your case note at GDH&S and will be used at the discretion of your treating clinicians Any treatment plan, intervention or advice based-on our potential findings is solely up to your Consultant.

By signing this form, you consent to the Study Doctor and his or her staff collecting and using your personal data for the study. This includes your date of birth, sex, ethnic origin and personal data on your physical condition. Your consent to the use of your Study Data does not have a specific expiration date. By signing this form you consent to the use of Study Data as described in this form.

HOW WILL MY CONFIDENTIALITY BE PROTECTED?

Special precautions are taken to ensure the research study is carried out with a high degree of confidentiality. If you agree to participate in the study, a code that is specific to you will be used to label your impressions, dental casts and Study Data and identify all results that are recorded at the University of Glasgow. This coding of information is to ensure that the results are kept confidential by keeping your identity and the results separate.

Impressions and Study Data will not include your name, address or hospital number. Only the Study Doctor at Glasgow Dental Hospital has access to the code key that connects your Study Data to you. The Study Doctor is responsible for handling of your Study Data in accordance with applicable Data Protection law(s). Please note, the results of the study may be published in medical literature, but you will not be identified.

CAN I WITHDRAW MY CONSENT?

If you decide to participate in the study, you are free to withdraw your consent for use of the impressions taken at any time. If you choose to withdraw your consent, you will not be disadvantaged in any way, including dental treatment and care you are entitled to receive. If you withdraw your consent, your impressions will be destroyed. The University may still use Study Data obtained before you withdrew your consent.

WHO SHOULD I CONTACT FOR INFORMATION OR HELP?

If you have any further questions about this study, please discuss this in the first instance with:

Prof Colin A. Murray

Professor in Restorative Dentistry/Honorary Consultant
Glasgow Dental School & Hospital
378 Sauchiehall Street
Glasgow, G2 3JZ
Tel: 0141 211 9626

Mr Khaled Ahmed

Clinical Academic Fellow/Honorary SHO
Glasgow Dental School & Hospital
378 Sauchiehall Street
Glasgow, G2 3JZ
K.Ahmed@dental.gla.ac.uk

WHO SHOLUD I CONTACT IF I HAVE ANY COMPLAINTS ABOUT THE STUDY?

If you have any complaints about the study, please discuss them with:

Mr Lee Savarrio

Consultant in Restorative Dentistry
Glasgow Dental Hospital & School
378 Sauchiehall Street
Glasgow, G2 3JZ
Lee.Savarrio@ggc.scot.nhs.uk

Thank you for taking the time to read this invitation.

Appendix 3: Participant's tooth wear study consent form

CONSENT FORM- Tooth Wear: 3D Scanning

A Study of Tooth Wear (September 2010 v.2)

PATIENT LABEL

Patient Identification Number for this trial: _ _ _ _ _ _ _ _ _ _ _ _ _

Name of researchers

Mr Khaled Ahmed, Glasgow Dental Hospital and School

Prof Colin Murray, Glasgow Dental Hospital and School

Dr John Whitters, Glasgow Dental Hospital and School

1. I confirm that I have read and understand the information sheet dated September 2010 (version 1) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐
3. I consent to the taking of impressions of my teeth for monitoring my toothwear condition☐
4. I agree to allow the analysis of the information obtained from the questionnaire for research purposes ☐
5. I agree to my General Dental Practitioner being informed of my participation in the study☐
6. I agree to take part in the above study. ☐
7. I confirm that I have received a signed copy of this information and consent form to keep. ☐

______________________ ______________________

Name of Patient Signature Date

______________________ ______________________

Researcher Signature Date

One copy to be retained by patient, one copy to be placed in the patients' notes and one copy to be retained in study file.

Appendix 4: Detailed patient questionnaire.

Patient Questionnaire

Please answer the following questions by crossing one box for each question:

1. How long have you been aware of your **tooth wear** condition?(*tick **one** box)*

   ☐ **Less than a year**
   ☐ **1 – 5 years**
   ☐ **6 – 10 years**
   ☐ **More than 10 years**

2. What is your **main** concern regarding your condition? ***(tick all that apply)***

   ☐ **Aesthetics/Cosmetics**
   ☐ **Sensitivity/Pain/ Discomfort**
   ☐ **Ability to Eat/Drink**
   ☐ **Speech**
   ☐ **Longevity/Survival/Prognosis of teeth**
   ☐ ***Other,*** *please specify:*

3. On a scale of **1 – 10**, how would you grade your **level of concern**?

   ☐ **1 – 3:** *not concerned*
   ☐ **4 – 6:** *slightly concerned*
   ☐ **7 – 9:** *concerned*
   ☐ **10:** *extremely concerned*

4. Do you suffer from **any** of the following? (*cross as appropriate*):

   ☐ **Excessive vomiting**
   ☐ **Eating disorders (Anorexia nervosa/Bulimia)**
   ☐ **Gastroesophygeal reflux disorder (GERD)**
   ☐ **Frequent heart burn/Indigestion**
   ☐ **Frequent use of antacids**
   ☐ **Sjorgen's Syndrome**
   ☐ **Depression** *(Including Bipolar Disorder)*
   ☐ **Insomnia**
   ☐ **Received radiation therapy of head and neck**
   ☐ **Frequent headaches**
   ☐ **Frequent use of pain killers**
   ☐ **Arthritis** *(Osteo, Rheumatoid..etc)*
   ☐ **Joint pain**
   ☐ **Dry mouth**
   ☐ **Dry eyes**
   ☐ **None of the above**

5. Have you ever been prescribed with any Anti-Depressant medication?
   - ☐ **Yes**
   - ☐ **No**
   - ☐ **Unsure**

6. Would you describe your lifestyle as being **stressful**?
   - ☐ **Yes**
   - ☐ **No**
   - ☐ **Unsure**

7. If **Yes**; how would you grade your **level of stress** on a scale of **1 – 10?**
   - ☐ **1 – 3:** *not very stressful*
   - ☐ **4 – 6:** *slightly stressful*
   - ☐ **7 – 9:** *stressful*
   - ☐ **10:** *extremely stressful*

8. Do you have any of these **habits**?
   - ☐ Smoking, *please specify* ***number of cigarettes per day**:*
   - ☐ Chewing gum on a regular basis
   - ☐ Nail/Pencil biting
   - ☐ Lip/Cheek biting
   - ☐ **Unsure**

9. What is your weekly intake of **alcohol**? (*1 glass of wine/1 pint of beer=2 – 2.3 units of alcohol*)
   - ☐ *Males:* **Less than or equal to 21 units per week**
   - ☐ *Males:* **More than 21 units per week**
   - ☐ *Females:* **Less than or equal to 14 units per week**
   - ☐ *Females:* **More than 14 units per week**
   - ☐ **Nil**

10. How often do you consume **carbonated/fizzy drinks** per week?
   - ☐ **Once every week**
   - ☐ **Three times a week**
   - ☐ **Everyday**
   - ☐ **Nil**

11. How much **carbonated/fizzy drink** do you consume per week?
   - ☐ **1 – 3 cans per week**
   - ☐ **4 – 7 cans per week**
   - ☐ **8 – 14 cans per week**
   - ☐ **More than 14 cans per week**
   - ☐ **Nil**

12. How <u>often</u> do you consume **fruit juices** per week?
- ☐ **Once every week**
- ☐ **Three times a week**
- ☐ **Everyday**
- ☐ **Nil**

13. How <u>much</u> **fruit juices** do you consume per week?
- ☐ **1 – 3 glasses per week**
- ☐ **4 – 7 glasses per week**
- ☐ **8 – 14 glasses per week**
- ☐ **More than 14 glasses per week**
- ☐ **Nil**

14. How <u>many</u> portions of **fruit** do you consume per week? *(1Medium sized fruit = 1 portion)*
- ☐ **Less than or equal to 7 portions per week**
- ☐ **8 - 14 portions per week**
- ☐ **15 - 35 portions per week**
- ☐ **More than 35 portions per week**
- ☐ **Nil**

15. Do you **Grind** your teeth during the day/night?
- ☐ **Yes**
- ☐ **No**
- ☐ **Unsure**

16. Do you **Clench** you teeth during the day/night?
- ☐ **Yes**
- ☐ **No**
- ☐ **Unsure**

17. Any **grinding sounds** during sleeping noted by bed partner?
- ☐ **Yes**
- ☐ **No**
- ☐ **Unsure**

18. Do you suffer from **jaw pain/discomfort** in the morning?
- ☐ **Yes**
- ☐ **No**
- ☐ **Unsure**

19. If **YES**, when did this **pain/discomfort** first start?
- ☐ **Less than 1 year ago**
- ☐ **1 – 5 years ago**
- ☐ **6 – 9 years ago**
- ☐ **More than 10 years ago**

20. Did you experience any **stressful events** prior to the start of the **pain/discomfort**?
    - ☐ **Yes**
    - ☐ **No**
    - ☐ **Unsure**

21. Any **jaw stiffness** in the morning?
    - ☐ **Yes**
    - ☐ **No**
    - ☐ **Unsure**

22. Any **limitation** in jaw movements?
    - ☐ **Yes**
    - ☐ **No**
    - ☐ **Unsure**

23. Frequent jaw **clicking** sounds?
    - ☐ **Yes**
    - ☐ **No**
    - ☐ **Unsure**

24. History of **jaws locking**/Unable to open or close your mouth?
    - ☐ **Yes**
    - ☐ **No**
    - ☐ **Unsure**

25. Do you suffer from **neck pain/discomfort** in the morning?
    - ☐ **Yes**
    - ☐ **No**
    - ☐ **Unsure**

26. History of Head and Neck **injuries/accidents**?
    - ☐ **Yes,** *please specify:*
    - ☐ **No**
    - ☐ **Unsure**

27. How <u>many</u> times a day do you **brush** your teeth?
    - ☐ **Less than once a day**
    - ☐ **Once a day**
    - ☐ **Twice a day**
    - ☐ **After each meal**
    - ☐ **More than 3 times a day**

28. How long do you **brush** your teeth?
   - ☐ **Less than 1 minute**
   - ☐ **1 - 3 minutes**
   - ☐ **More than 3 minutes**
   - ☐ **Unsure**

29. How do you **brush** your teeth?
   - ☐ **Mainly Horizontal strokes**
   - ☐ **Mainly Vertical strokes**
   - ☐ **Mainly Circular strokes**
   - ☐ **Unsure**

30. Do you use any **whitening/bleaching/abrasive** toothpaste?
   - ☐ **Yes**
   - ☐ **No**
   - ☐ **Unsure**

31. Did you previously receive any **dietary advice** regarding your tooth wear condition?
   - ☐ **Yes**
   - ☐ **No**
   - ☐ **Unsure**

32. Did you previously receive any **treatment** for your tooth wear condition?
   - ☐ **I haven't received any treatment**
   - ☐ **Splint/Stent/Night-guard**
   - ☐ **Hypnotherapy**
   - ☐ **Fillings**
   - ☐ **Crowns/Bridges**
   - ☐ **Medication for Gastric reflux**
   - ☐ **Stopped taking fizzy drink**
   - ☐ **Treatment for frequent vomiting**
   - ☐ **Impressions for models to monitor tooth wear**
   - ☐ **Unsure**

- **Please state any current or previous medical conditions/problems:** *(such as diabetes, asthma, high-blood pressure, arthritis, cardiac/heart, respiratory/lung, renal/kidney***,** *liver/hepatic conditions, previous surgeries)*

Published Papers

The psychology of tooth wear

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ABSTRACT

Aim: To review the main psychological and mental conditions that are manifested dentally in the form of tooth wear. These conditions include depression, eating disorders, and alcohol and drug use disorders. The paper will also review the comorbidity of these conditions and the relevance of other medical conditions and lifestyle factors, such as gastroesophageal reflux disorder, smoking and diet, in the expression of tooth wear. Conclusion: A holistic, multidisciplinary, healthcare approach is required in management of tooth wear patients with underlying mental health disorders. Dentists and Dental Care Professionals can have an important role in identifying these mental disorders through the observed tooth wear. They can also play a key role in monitoring patients' response and compliance to medical treatment through the monitoring of tooth wear progression and expression.

KEY WORDS: depression, eating disorders, alcohol abuse, addiction, tooth wear, bruxism, erosion

Introduction

Tooth wear, also referred to as tooth surface loss (TSL) or non-carious TSL, has been defined as the "pathological loss of tooth tissue by a disease process other than dental caries".[1] The etiological factors of tooth wear include attrition, erosion and/or abrasion. Attrition is tooth structure loss due to tooth–tooth contact, while erosion is TSL due to chemical/acid action from intrinsic and/or extrinsic factors and abrasion is caused by physical wear from factors other than tooth–tooth contact.[2-8] It is estimated that the percentage of adults presenting with severe tooth wear increases from 3% at the age of 20 to 17% at the age of 70.[9,10]

Although tooth wear can have detrimental dental effects, yet it can also serve as an important screening and diagnostic criteria for identifying a number of mental and psychological conditions and disorders.[11-15] Mental health is a serious issue, with stress, anxiety and depression accounting for the loss of 56 million working days in the UK due to sickness absences at an estimated cost of £4.1 billion.[16] Across Europe, the UK has the highest prevalence rates of common mental disorders among general practice attendees, at 18.8% for men and 18.2% for women.[17] Furthermore, according to the 2007 Adult Psychiatric Survey of England, covering 13,171 households, 15.1% of interviewed adults demonstrated clinically significant neurotic symptoms in the week prior to the interview.[18] Dentists and Dental care professionals (DCPs) have a key role in identifying certain mental conditions and managing/referring them to the appropriate healthcare professional/s. This role can be achieved through the successful diagnosis of the etiology underlying the observed tooth wear, which in many cases is mentally or psychologically derived.

The aim of this paper is to review the main psychological and mental conditions that are manifested dentally in the form of tooth wear. The paper will also review the comorbidity of these conditions and the relevance of other medical conditions and lifestyle factors, such as gastroesophageal reflux disorder (GORD), smoking and diet, in the expression of tooth wear.

Depression

The World Health Organization (WHO) in the International Classification of Diseases (ICD-10) defined depression as a mental disorder characterized by a depressed mood, loss of interest and enjoyment, and reduced energy leading to increased fatigability and diminished activity.[19] Other common symptoms of depression include: reduced self-esteem and self-confidence, ideas of guilt and unworthiness, ideas of acts of self-harm or suicide, disturbed sleep and diminished appetite. On the other hand, stress is defined as any threat to the homeostasis of an organism, whether it is physical, psychological, environmental, or derived from within the individual.[20] Moreover, stress can be a predisposing factor of depression through depletion of serotonin, dopamine and norepinephrine.[21,22]

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It is estimated that 9% of British adults suffer from mixed anxiety and depression; making it the most commonly diagnosed mental disorder in the UK.[18,23] Eleven percent of the Scottish population aged 15 and overuse antidepressants on a daily basis.[24] Depression has a high recurrence rate with 50% of depression patients suffering from a second major episode.[25] Furthermore, 50% of patients initially diagnosed with depression had a persistent diagnosis of the condition 1 year later.[26] There is also evidence to support an association between stress, depression and GORD. A study of 4600 participants demonstrated a significantly higher prevalence ($p < .001$) of anxiety, depression and hostility in participants with GORD symptoms versus those without.[27] The results of this study agree with those obtained by others.[28-31] Furthermore, 30% of people with depressive episodes experience lifetime alcohol use problems[32] and are twice as likely to smoke compared to those without any neurotic disorders.[33]

Table 1. Main mental health disorders, potential comorbidity factors and resultant signs of tooth wear expected.

Mental Disorder	Comorbidity	Tooth wear signs
Depressive disorders	• GORD	◦ Primary: attrition
	• Alcohol	◦ Secondary: intrinsic and extrinsic erosion
	• Smoking	
Eating disorders	• Depression	◦ Primary: intrinsic erosion
	• Alcohol	◦ Secondary: attrition and extrinsic erosion
	• Smoking	
	• Drug use	
	• Acid-rich diet	
Alcohol use disorders	• Depression	◦ Primary: extrinsic erosion
	• GORD	◦ Secondary: attrition and intrinsic erosion
Drug use disorders	• Depression	◦ Primary: attrition
	• Alcohol	◦ Secondary: extrinsic erosion
	• Acid-rich diet	

Tooth wear and depression

Studies have demonstrated an association between depression, stress, anxiety, and tooth wear. A cross-sectional survey of 13,057 participants in the UK, Germany, and Italy reported that participants who suffered from anxiety, stress, smoking, and heavy alcohol drinkers were at a higher risk of reporting sleep bruxism with 8.2% of participants grinding their teeth at least weekly.[34] Another study involving 1784 participants, aged between 30 and 55 years, examined the relationship between reported bruxism and stress experience using questionnaires.[35] The study demonstrated a significantly positive association between bruxism and severe stress experiences. Psychosocial job stress, low social support from supervisors or colleagues and high-depressive symptoms demonstrated a significantly increased risk of bruxism in a study involving 2680 participants.[36] These findings tend to agree with those of other studies demonstrating a significant association between tooth wear, depression, stress, and emotional stability.[14,37-42]

There is an evident comorbidity between depression, GORD, alcohol abuse and smoking, with tooth wear being one of the main dental manifestations of such disorders (Table 1).

GORD is often first diagnosed by dentists through observation of tooth wear.[43,44] A systematic review of the existing literature was carried out to assess the relationship between GORD and dental erosion.[45] The review concluded that dental erosion was present in 5–47.5% of GORD patients. Research has also demonstrated that nocturnal bruxism can be secondary to acid reflux episodes.[46-48] There is also some evidence supporting an association between GORD, alcohol intake and smoking.[49,50] Furthermore, nicotine-intake is significantly associated with bruxism, with bruxers twice as likely to report heavy smoking.[51,52]

Eating disorders

The two main eating disorders (ED) of importance to dentistry are anorexia nervosa and bulimia nervosa. According to the ICD-10, anorexia nervosa is a disorder characterized by deliberate weight loss, induced and/or sustained by the patient and occurring most commonly in adolescent girls and young women.[19] The ICD-10 further states that one of the definitive diagnostic criteria for anorexia nervosa is the presence of a body-image distortion in the form of a specific psychopathology. There may be associated depressive or obsessional symptoms, as well as features of a personality disorder. On the other hand, bulimia nervosa is a syndrome characterized by repeated bouts of overeating and an excessive preoccupation with the control of body weight, leading the patient to adopt extreme measures to mitigate the "fattening" effects of ingested food. Bulimia nervosa shares the same psychopathology, age and sex distribution as anorexia nervosa, but the age of presentation tends to be slightly older.[19]

In the UK, anorexia nervosa is reported to affect 1.9% of women and 0.2% of men, and 0.5% and 1%, respectively, for bulimia nervosa.[53] The most common comorbid psychiatric condition in ED is major depression.[54-56] Moreover, the average number of weekly vomits of 371 ED patients was reported to be between 5.13–9.17 times per week, with 26.3–35.2% of ED patients reporting drug/substance abuse.[57] High rates of alcohol use disorders, smoking and nicotine dependence are prevalent among ED patients.[58-62] Furthermore, a study of 78 ED patients and 32 healthy controls demonstrated that ED patients consumed on average between 16.3–39.5 cans of diet beverages per week compared to 7.4 cans for healthy controls.[63]

Tooth wear and eating disorders

Dental erosion can be frequently encountered in ED patients. It is estimated that between 35–38% of ED patients suffer from tooth erosion.[64,65] A matched case-control study comparing the oral health of 54 ED patients and 54 healthy participants, matched for gender and age, demonstrated that the prevalence of severe tooth wear was significantly higher ($p = .005$) in ED patients at 38% compared to 11% of controls.[66] Tooth wear is particularly evident on the palatal surfaces of anterior and posterior teeth[67,68] and is caused by the purging behavior of gastric acidic contents[69,70] and the elevated consumption of acidic carbonated drinks to boost energy or decrease the reflex hunger stimulus.[71-73] The association between ED, alcohol consumption, drug use and smoking can further exacerbate tooth wear. The psychological stress, high comorbidity of depression in ED and smoking can trigger bruxism, as previously discussed.[14] The association between alcohol, drug use and tooth wear will be discussed later in this paper.

The chances of dentists and DCPs coming across ED patients are quite high,[74] hence they have a crucial role in identifying ED patients and appropriately managing them. On the other hand, a study involving 202 dentists and 367 dental hygienists, demonstrated low scores concerning knowledge of oral and physical cues of anorexia and bulimia among study participants.[75] More dental hygienists than dentists correctly identified oral manifestations of ED ($p = .001$). Additionally, female dentists tend to have greater knowledge of oral manifestations of ED compared to male dentists ($p = .001$).[76] Eighty six percent of dentists reported that they needed more training in dental management of patients with ED, according to a study involving 258 dentists.[77]

Alcohol use disorders

The WHO adopted the term *'alcohol use disorders'* to denote mental, physical and behavioral conditions of clinical relevance associated with the use of alcohol.[78] Alcohol use disorders include acute intoxication, harmful use, dependence syndrome, withdrawal syndrome, psychotic disorders and amnesic syndrome. Disorders of special interest are: harmful use and dependence syndrome. Harmful use is defined as a pattern of use that causes damage to health whether physical or mental. On the other hand, dependence syndrome is a cluster of psychological, behavioral and cognitive phenomena in which substance use (such as alcohol or psychoactive drug use) takes a higher priority than other behaviors despite harmful consequences.[19]

According to the Prime Minister's Strategy Unit interim analytical report of 2003, it is estimated that in Britain there are 1.8 million people who are very heavy consumers of alcohol, at 50 units for men and 35 units for women per week.[79] The report also estimated that 7% of Britain's adult population is alcohol dependent. A quarter of British adults (26%) were assessed as being harmful/hazardous alcohol drinkers.[23]

Furthermore, alcohol dependency was associated with neurotic symptoms, major depression and GORD. Neurotic symptoms are present in 30% of those with an alcohol dependency syndrome.[33] The presence of an alcohol use disorder doubled the risk of presence of major depression.[80] Similarly, GORD symptoms are present in patients with alcohol dependency.[50,81]

Tooth wear and alcohol use disorders

Dental erosion is prevalent amongst patients with alcohol dependency and individuals with high wine consumption.[11,82] A study demonstrated that 49.4% of alcohol dependency patients undergoing rehabilitation suffered from enamel and/or dentine erosion lesions.[83] The tooth wear risk of alcohol use disorders arises, not only from the acidic erosive potential of alcohol, but also from the high comorbidity between alcohol, depression, GORD and smoking, as previously discussed.

Current practices and intentions to provide alcohol-related health advice in primary dental care were examined in a study that involved 175 General Dental Practitioners (GDPs) randomly selected from across Scotland.[84] The results of the study demonstrated that GDPs had relatively poor knowledge on recommended alcohol consumption guidelines and associated risk. Furthermore, GDPs demonstrated a low intention to provide alcohol related advice and exhibited a lack of positive attitude and efficacy towards delivering such advice.

Drug use disorders

The definition of drug use disorders have been previously discussed in reference to harmful use and dependency syndrome definitions, present in the WHO's ICD-10.[19]

In Britain, between 3.7–4% of the population is considered to be drug dependent.[23,33] The 2003, Prime Minister's Strategy Unit's Drugs report stated that the UK had over three million drug users.[85] The report estimated that, in England and Wales alone, there were over one million amphetamine and ecstasy users in the previous year, with half of them reporting use in the past month. Amphetamines, methamphetamines (MAP) and ecstasy (3,4-methylenedioxymethamphetamine, MDMA) are psychostimulant drugs possessing hallucinogenic and excitatory properties caused by their dopaminergic, serotonergic and adrenergic systemic effects.[86] Moreover, MDMA is frequently used in-combination with cannabis (71%), amphetamine (29%) or cocaine (25%).[87]

The comorbidity of drug and alcohol abuse, depression and EDs is well documented. Psychiatric disorders are present in 45% of drug dependents.[23] The use of psychostimulants is significantly higher in EDs patients ($p < .001$) compared to healthy controls, at 17.2 and 6.2%, respectively.[88] MDMA users are at higher risk (53% of users) of developing psychopathological disturbances, with depression reported as the most frequent disturbance.[89] Furthermore, a study including 3503 participants reported that 66% of ecstasy users consumed alcohol in combination with MDMA.[87] Another study reported that 93% of MDMA users consumed a mean of three cans of carbonated drinks per "trip".[90]

Tooth wear and drug use disorders

A study of 301 MAP dependents demonstrated that 22% of them have been aware of bruxing behavior and tooth erosion for the past 6 years.[91] Furthermore, MAP users who snorted the drug had a significantly higher prevalence of tooth wear ($p = .005$) in their anterior maxillary teeth, when compared to users who injected, smoked or ingested the drug. MDMA users had a higher prevalence and severity of tooth wear (60%) when compared to nonusers (11%), with 93% of MDMA users reporting xerostomia and 89% of them reporting clenching or grinding after taking the drug.[90] The high consumption of carbonated drinks and alcohol (to combat dehydration) and bulimic episodes associated with drug use further compound the present tooth wear through the introduction of an erosive element.

Dental disease may provide a stable and specific medical marker for identifying MAP users, with dentists capable of participating in collaborative care of MAP users through early detection of drug-related oral/dental cues.[91]

Discussion

Patients with mental health disorders comprise a significant cohort of society that dentists and DCPs will frequently encounter in practice. The management of this patient cohort can be challenging, both medically and dentally. Dentists and DCPs can have an important contribution towards the well being of these patients through early identification of present oral manifestations, appropriate management of the patient and successive oral state monitoring.

Early identification emanates through knowledge and understanding of physical and oral/dental signs, with tooth wear being one of the major ones, of potentially underlying medical conditions. On the other hand, management of patients with mental health disorders can be challenging. Attempting to obtain an accurate patient history, to assist in identifying the underlying etiology, can be elusive and requires training. Hence, referral to an appropriate healthcare professional (General Medical Practitioner, Clinical Psychologist, Hypnotherapist, Psychiatrist, etc.) might be necessary for a definitive diagnosis and appropriate medical care. Furthermore, dental management can present its own challenges. Assessing and managing tooth wear falls under Primary Care provision as stated by the UK's General Dental Council's learning outcomes for registration, published in May 2011.[92]

On the other hand, patients with mental and psychological conditions can also fall under the provision of Special Care Dentistry according to the Joint Advisory Committee of Special Care Dentistry, as patients who have *"a physical, sensory, intellectual, mental, medical, emotional or social impairment or disability or, more often, a combination of a number of these factors"*.[93]

Further complicating matters, many of these patients present with severe/advanced tooth wear requiring complex treatment plans and potentially a full-mouth rehabilitation approach. With the shortage of present dental literature related to rehabilitation of tooth wear of suitable scientific quality to be included within critical reviews, and the absence of documented outcomes of various tooth wear rehabilitation approaches,[94] a definitive treatment plan can be challenging and referral to Secondary/Specialist Care becomes inevitable. As a result, a clear and definitive dental care pathway for tooth wear patients with mental health disorders seems to be lacking.

Finally, dentists and DCPs can assist in monitoring patients' response and compliance to undergoing medical treatment/therapy through routine monitoring of tooth wear progression. This can be accomplished through the use of dental casts and intraoral clinical examination to identify the rate of progression of tooth wear. Moreover, recent advances in 3D scanning technology can offer an early and accurate means of monitoring tooth wear.[95]

Conclusion

A holistic, multidisciplinary, healthcare approach is required in management of tooth wear patients with underlying mental health disorders. An understanding of these disorders would enable dentists and Dental Care Professionals (DCPs) to identify them through the observed tooth wear and diagnosis of the wear's underlying aetiology. Appropriate management of this significant patient cohort, through treatment and/or referral, requires clarification. Dentists and DCPs can further play a key role in monitoring patients' response and compliance to medical treatment through the monitoring of tooth wear progression.

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Declaration of interest

The author declares that there was no conflict of interest present at the time of the undertaking of this review.

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A prospective survey of secondary care tooth wear referrals: demographics, reasons for concern and referral outcomes

IN BRIEF

- Investigates tooth wear referrals to secondary care.
- Provides insight into patients' perception of their tooth wear condition, their main concerns and expectations.
- Demonstrates an association between tooth wear and socioeconomic deprivation in patients.

RESEARCH

K. E. Ahmed,*[1] C. A. Murray[2] and C. J. Whitters[3]

Aim To provide a descriptive investigation of general dental practitioners' (GDPs) referrals to Glasgow Dental Hospital and School for management of tooth wear. **Materials and methods** One hundred and twenty-four patient-referrals were reviewed over a 12 month period. A questionnaire was also completed by patients and three reviewing consultants to identify patient demographics, patient perception, consultant's diagnosis and referral outcome. **Results** Overall survey return-rate was 67% of 124 included referrals. Males represented 72% of referrals compared to 28% for females ($p = 0.001$). A significant percentage of patients inhabited the most-deprived areas (59%, $p = 0.002$). Sixty-one percent of patients were aware of their tooth wear within the past five years. Aesthetics was the primary concern for 54% of patients ($p = 0.001$). Attrition was the main aetiology of tooth wear in 51% of referrals ($p = 0.001$). Ninety-two percent of patients ($n = 76/83$) did not require specialist treatment and were consequently returned to their GDP, referred for hypnotherapy or reviewed later. **Conclusion** There was a significant association between social deprivation and tooth wear in GDP referrals to a secondary care dental facility. Males aware of their tooth wear for the preceding five years, presenting with appearance as their main complaint and displaying evidence of attrition were more likely to be referred by GDPs for specialist management or advice.

INTRODUCTION

Tooth wear, also referred to as tooth surface loss (TSL) or non-carious tooth surface loss (NCTSL), has been defined as pathological tooth tissue loss by a process other than dental caries.[1] Tooth wear has a measurable impact on patient satisfaction in terms of appearance, pain levels, oral comfort, general performance, chewing and eating capacity.[2,3] The main aetiological factors of tooth wear are erosion, attrition and abrasion.

Dental erosion is tooth surface loss of enamel and/or dentine caused by chemical/acid action from intrinsic, extrinsic and/or environmental factors not involving bacterial action.[4,5] Dental erosion may arise from conditions including gastroesophageal reflux and eating disorders or from dietary factors such as a high intake of carbonated drinks, alcohol, fruit or fruit juice consumption.[6-8] Attrition is caused by friction between opposing teeth and is frequently associated with para-functional temporomandibular or lingual habits.[9] Such activities may include alone or in combination: jaw clenching, tooth grinding/bruxism, tooth tapping, cheek, lip or tongue biting, tongue thrusting, licking lips, tongue protrusion, gum chewing, object biting, hyper-salivation/swallowing or jaw posturing.[10,11] Abrasion is the pathological wearing of dental hard tissue through mechanical forces by repeated introduction of foreign bodies into the oral cavity in contact with the dentition.[12] There are a number of aetiological factors associated with abrasion with the most common relating to oral hygiene care, primarily tooth brushing and use of dentifrices.[13,14] Abrasion may also occur due to certain habits such as pipe smoking, improper use of dental floss and toothpicks, chewing tobacco or biting pencils, pens and fingernails.[15,16]

The percentage of adults presenting with severe tooth wear has been confirmed to increase from 3% at the age of 20 to 17% at the age of 70, thereby demonstrating a significant relationship with increasing age.[17] The Adult Health Survey of 2009 estimated that 77% of dentate adults in England, Wales and Northern Ireland demonstrated signs of tooth wear extending to dentine in their anterior teeth, with prevalence of tooth wear increasing with age.[18] Several studies have demonstrated a relationship between gender and tooth wear. Indeed, males are associated with a higher prevalence of tooth wear compared to females.[18-20]

Studies investigating the association between socioeconomic status and tooth wear have mainly focused on dental erosion in children and adolescents. Those studies demonstrated a higher prevalence of dental erosion among patients from deprived socioeconomic groups when compared to less deprived cohorts.[21-23] Moreover, children living in northern regions of the UK are twice as likely to suffer from dental erosion compared to those living in London and the South-East.[24] In contrast, other studies have identified a higher prevalence of dental erosion in less deprived populations when compared to more deprived cohorts.[25] Further investigation is needed to clarify the relationship between socioeconomic deprivation and tooth wear in adults and whether socioeconomic status can be considered as a risk factor in adults.

According to the General Dental Council (GDC), assessment and management of tooth wear falls under the provision of primary care, as outlined in the May 2011 published

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learning outcomes upon registration, (LO number 1.12.1).[26] However, current tooth wear assessment regimes generally do not provide information as to whether the detected tooth wear is pathological and potentially requiring restorative intervention, or physiological as a natural result of age and requiring no clinical intervention.[27] The treatment decision-making process is further complicated by lack of agreement upon acceptable thresholds in rates of tooth wear.[28,29] This might explain limited availability of published studies related to rehabilitation of tooth wear that are of suitable scientific quality to be included within critical reviews and documented outcomes of various tooth wear rehabilitation approaches.[30,31] Hence, with the lack of an evidence-based tooth wear management consensus, tooth wear management can become extremely challenging.

Nevertheless, recent technological advances in 3D imaging may potentially provide an objective quantitative means to measure tooth surface loss that rely on physical measurements rather than relying upon clinical subjective indices.[32,33] This objective assessment of tooth wear is made possible through the rapid capture of 3D digitised images of a patient's dentition, whether directly *in vivo* or *in vitro* from dental casts.

The aim of this prospective survey was to provide a descriptive investigation of the patient cohort referred by general dental practitioners (GDPs) within Scotland to a secondary care setting for management of tooth wear and identify outcomes of the patient referral pathway. The survey would assist in identifying associations between certain patient factors, such as socioeconomic status, gender, age, aetiology of tooth wear, treatment needs, and their referral to secondary care and whether they can be considered as tooth wear risk factors that can aid clinicians in diagnosing and appropriately managing tooth wear. Furthermore, the referral outcome would assist in further developing current secondary care referral pathways through potential improvements to referral system and/or GDP awareness.

MATERIALS AND METHODS

A prospective survey study was undertaken at Glasgow Dental Hospital and School (GDH&S) during 1 April 2010 to 30 April 2011. Ethical approval was provided by the West of Scotland Ethics Committee (10/S0709/59).

A tooth wear analysis questionnaire was formulated comprising three main sections (Appendix 1). Section A was completed by the screening auditor to collect patient demographic data and referral information. Section B was completed by the patient during their restorative specialist consultation and addressed patient-perception of their tooth wear condition. Section C was completed by the receiving consultant to record diagnosis and referral outcome. Only patients referred by GDPs solely for tooth wear management and assessment were included in this study. If there were other reasons for referral stated in the referral letter, then the patient was excluded from study participation. A convenience sample of 124 referrals was calculated for inclusion in the study during the 12 month time period. Included patients were reviewed by three restorative dentistry consultants at GDH&S.

Before initial consultation, patient records were reviewed to identify patients referred by GDPs to GDH&S for tooth wear management. Once tooth wear referrals were identified and Section A of the questionnaire completed, the study questionnaire was attached to patients' records and completed by the patient and receiving restorative consultant. Questionnaires were then collected at the end of each new patient consultation clinic for analysis.

In order to determine socioeconomic deprivation level of referred patients based upon the Scottish Index for Multiple

Table 1 Distribution of referred tooth wear patients within most deprived to least deprived categories, using SIMD quintiles based on patients' postcode data

SIMD quintile	Number of referrals, n = 124
1 (most deprived)	38 (31%)
2	26 (20%)
3	21 (17%)
4	10 (8%)
5 (least deprived)	14 (11%)
Blank (information not given)	15 (12%)

Table 2 Distribution of tooth wear referrals based on age groups.–

Age group (years)	Number of referrals, n = 124
19–30	20 (16%)
31–41	31 (25%)
42–52	31 (25%)
53–63	27 (22%)
64–79	15 (12%)

Table 3 Distribution of patient concerns when requesting a secondary care referral for their tooth wear

Main reason of complaint	Males, n = 57	Females, n = 23	Total, n = 80
Aesthetics	35 (61%)	8 (35%)	43 (54%)
Function	10 (18%)	0	10 (12%)
Sensitivity	7 (12%)	13 (57%)	20 (25%)
Other	5 (9%)	2 (9%)	7 (9%)

Table 4 Tooth wear patient referral outcomes at GDH&S

Referral outcome	Number of referrals, n = 83
Return to GDP	39 (47%)
Hypnotherapy	23 (28%)
Review	14 (17%)
Secondary care treatment	7 (8%)

Deprivation (SIMD) Scottish Health Board quintiles[24] the patient post-code data was recorded.

Statistical analysis was performed using SPSS™ (release 18.0.0) and MiniTab™ (release 15.1.30.0.). In accordance with the determined sample size, a Fishers exact test was used to test differences between proportions.

RESULTS

One hundred and twenty-four patient referrals for tooth wear were identified and included in this pilot study. Eighty questionnaires were completed by patients for part B and 83 questionnaires completed by the reviewing consultant for part C. The over-all return rate of included tooth wear study referrals was 67% (n = 83).

There was a significant difference (p = 0.001) between the number of male and female patients referred for tooth wear management, with 72% (n = 89) of tooth wear referrals being male compared to 28% (n = 35) female. A greater number of referred patients (59%) inhabited the most deprived areas (quintiles one and two, according to the Scottish Index for Multiple Deprivation), this being significantly higher (p = 0.002) than those inhabiting the least deprived areas (Table 1). Attrition was mentioned as the underlying aetiological cause of tooth wear in 40% (n = 50) of GDP referral letters, followed by erosion (15% n = 18) and 10% (n = 12) identifying a combination of attrition and erosion. There was no mention of the aetiological cause of tooth wear in 35% (n = 44) of GDP referral letters. In 90% (n = 121) of patient referrals, no dental study casts were sent with the GDP referral. Seventy-two percent of referred patients were between the ages of 31 and 63, which represented a significant difference (p = 0.001) when compared to other age groups (19–30 and 64–79) within the study (Table 2).

The percentage of patients previously aware of their tooth wear condition for less than six years was significantly higher (p = 0.007, n = 49) at 61% compared to those aware of the condition for six to ten years (n = 17, 21%) or over ten years (n = 14, 18%). The number of tooth wear patients either concerned or severely concerned by their tooth wear condition was significantly greater (n = 71, p = 0.001) than those not concerned by the condition (n = 9, 11%,). Aesthetics was the principal reason for concern in 54% of study patients (95% C.I = 40–60%, p = 0.001) (Table 3). Fewer patients reported sensitivity or function as their main reasons for concern at 25% and 12% respectively.

Attrition was diagnosed by restorative specialists as the primary aetiological cause of tooth wear in 51% of referrals (n = 42). This was significantly higher (p = 0.001) than tooth wear diagnosed as a result of erosion (17%, n = 14) or a combination of attrition and erosion (32%, n = 27). Seventy-eight patients, representing 92% of returned referral questionnaires, were assessed as not requiring specialist treatment intervention and were instead returned to their GDP with a treatment plan, referred for a course of hypnotherapy to address underlying bruxism behaviour or seen for further review within the secondary care setting to monitor tooth wear progression (Table 4).

DISCUSSION

The aims of this pilot study were to provide a descriptive investigation of a patient cohort referred by GDPs to a secondary care setting for management of tooth wear and determine outcomes of the patient referral pathway. The overall patient return rate of the survey was 67%, which compares favourably to similar studies.[25] Limited consultation time and patients not attending on the day of consultation contributed towards the varying return rates.

Thirty-five percent of GDP patient referral letters examined in this study did not record any underlying aetiological causes for the observed tooth wear. Furthermore, 98% of referrals did not include diagnostic study casts that might potentially assist in identifying tooth wear progression over a given time period and presenting the receiving specialist with a baseline comparison.

The findings of this study demonstrate that referred tooth wear patients within this Scottish sub-population were more likely to be young to middle-aged males inhabiting socioeconomically deprived areas who were concerned by their tooth wear condition for which aesthetics was their main reason for concern. These findings are comparable to other studies investigating different geographical populations where males predominated GDP tooth wear referrals, aesthetics was the primary presenting complaint and socioeconomic deprivation and age were directly associated with tooth wear.[5,17,18,26]

An understanding of the demographics and needs of tooth wear patients will assist in delivering the appropriate care that these patients require and seek. Furthermore, identifying the various factors associated with tooth wear, such as bruxism, aesthetic concerns and socioeconomic deprivation, will help towards diagnosing and managing other underlying disorders that might be concomitant with tooth wear, such as stress, depression, eating disorders, alcohol and drug dependencies.[27] Indeed, in this study we identified a predominance of patients originating from lower socioeconomic groupings within the tooth wear referral cohort. This is of particular relevance to the population involved in this study as Glasgow suffers from a 30% increased rate of premature deaths compared to cities of similar socioeconomic deprivation distribution in the UK and more than half the excess deaths occurring in males under the age of 65 are directly related to alcohol and drugs.[28]

Referral to secondary care can be considered as part of the overall management process of tooth wear, through provision of a treatment plan or specialist clinical management of severe/advanced tooth wear cases. Interestingly, a substantial majority (92%) of referred tooth wear patients were identified as not requiring clinical specialist treatment. These findings tend to raise questions with regard to the extent of tooth wear management in primary care. Furthermore, the lack of mention of a diagnosed aetiological cause and lack of inclusion of study casts of the patient's dentition at an earlier time point might divest reviewing consultants of valuable diagnostic data. These findings imply a need for increased awareness among primary dental care providers with regard to management of tooth wear, which can be provided through continued professional development.

In order to further improve secondary care provision for tooth wear patients, a more specific tooth wear referral system needs to be implemented. This referral system needs to ensure the inclusion of the diagnosed, underlying aetiological factor(s) of the observed tooth wear and the patient's principal reason of concern contributing towards the referral. Furthermore, the referral letter should also mention any previous tooth wear management attempts carried out by the referring GDP, such as dietary advice, splint therapy, oral hygiene advice and/or composite build-ups. Dental casts taken previously can be sent with the referral letter or presented by the patient on the day of consultation, as this would present a baseline comparison to the patient's current dentition.

CONCLUSION

Based on the findings of this study, patients referred by general dental practitioners to Glasgow Dental Hospital and School for management of tooth wear are more likely to be males between the ages of 31–63 and inhabiting a socioeconomically deprived area. Generally, patients were aware of their tooth wear condition within the preceding five years and were either concerned or severely concerned by their condition with dental aesthetics being identified as the primary cause of concern. Attrition was determined to be the primary cause of tooth wear and the majority of referred patients did not require specialist intervention. The majority of tooth wear cases were returned to the referring dental practitioner with a treatment plan, referred for a course of hypnotherapy treatment or reviewed by a specialist for monitoring of tooth wear progression. Moreover, these findings highlight the need for increased awareness in primary dental care with regard to tooth wear management and development of current referral system in secondary dental care.

The authors declare that there was no conflict of interest present at the time of the undertaking of this study.

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