AN EVALUATION OF COMPUTER-BASED RADIOGRAPHIC METHODS IN ESTIMATING DENTAL CARIES AND PERIODONTAL DISEASES

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Abstract

Reductions in dental diseases have resulted in a need for more accurate diagnostic and monitoring methods. The purpose of this study was to 1) identify the best diagnostic technique, 2) investigate the main factors which limit its validity and reliabilty and 3) devise methods to improve its reliability and 4) investigate ways of automating its use for general dental practice.

From the literature review radiography was identified as the best current method with regard to validity, reliability, production of stable objective data and ease of use. However, irradiation geometry variations between serial films and subjective measurement errors were its principle limitations. Although an accurate semi-automatic caries measuring system exists, it is unsuitable for general practice due to lengthy operator interaction.

A series of computer-based experiments were devised to evaluate further the digital subtraction radiography technique (DSR); develop a new method using stored regions of interest (ROI) to reduce subjective measurement errors; investigate the feasibility of completely automatic image analysis. In addition, an in vitro caries experiment was designed to demonstrate the effects of irradiation geometry variation on lesion size and caries scores.

The results demonstrated that small variations in irradiation geometry can change radiographic scores. Misalignment of subsequent films

beneath a video camera can cause significant errors in the DSR technique. The stored ROI method reduced cement-enamel junction to alveolar crest measurement errors to standard deviation 0.15mm. A fully automatic method for recognising teeth and bone crests was demonstrated.

It was concluded that 1) radiography is currently the technique of choice, 2) a new significant methodological error for DSR has been demonstrated, 3) the subjective ROI method produced lower intra- and inter-examiner measurement errors compared to similar methods, 4) routine use of automatic methods may be feasible and should be investigated further and 5) standardised irradiation geometry is essential.

To Jane and Oliver

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Chapter 1 Introduction

This chapter examines the changing prevalence of dental diseases to see if there is any evidence to support the hypothesis that high risk groups exist in a population. Since diagnosis is a key element in measuring disease in populations and in individuals, the difficulty of establishing an accurate diagnosis is considered together with the effects of different disease prevalence levels.

1.1 Changing patterns of dental diseases

During the last 20 years a significant decline in caries experience has occurred in many industrialised countries; the reductions in children are of about 50% in five-year-olds, 40% in 12-year-olds and 33% in 15-year-olds (Allen et al 1983; Downer 1984; Renson 1986; Hugoson et al 1988a; Hugoson et al 1988b). Not only has the overall prevalence of caries fallen but the proportion of smooth surfaces affected (approximal, buccal and lingual) has declined more than occlusal caries. The latter is now the predominant caries site (Moller 1987). Concern has been expressed regarding a possible increase in the prevalence of root caries since people are retaining more of their teeth into old age (Katz 1990). However, uncertainty exits regarding the true prevalence of root caries due to the lack of comparability of data between surveys (Beck 1990).

As well as considering the prevalence of caries, it is also necessary to examine the rate of caries progression through enamel into dentine.

Progression generally proceeds slowly and many lesions may remain static in enamel or even remineralise (Berman and Slack 1973; Zamir et al 1976; Grondahl et al 1977; Ekanayake and Sheiham 1987; Hugoson et al 1988a; Hugoson et al 1988b). From a review of 13 papers on caries progression it was calculated that a 'mean' time of 3-4 years existed for radiographic lesion images to remain within enamel in permanent teeth (Pitts 1983a). In caries active individuals much shorter times were reported and Pitts (1983a) also stated that large numbers of lesions remained unchanged for long periods. In deciduous teeth the 'mean' time was probably shorter due to the thinner enamel caps, but Pitts was unable to provide a firm indication of progression rates in deciduous teeth due to the variable reporting methods of the investigators. Solanki (1987) demonstrated that the choice of different scoring systems can have a significant effect on progression rates and this, together with the small number of longitudinal surveys of deciduous teeth, probably accounts for the variation of reported rates.

More recently a study of caries progression in British schoolchildren has shown that rates in Britain have decreased since 1969 (Ekanayake and Sheiham 1987). Children examined between 1978 and 1982 had a higher proportion of carious lesions which did not progress and slower rates of progression than those examined using a similar radiographic technique between 1966 and 1969. Eleven per cent of outer enamel lesions progressed into dentine or to a filled state in 3 years in the 1978 group, compared to 29% in the 1966-1969 group. Similar findings have been reported by Hugoson et al (1988) who also commented that

"when caries prevalence is decreasing, more refined diagnostic measures should be used in order to make it possible to follow changes."

In the past, when caries prevalence and progression rates were higher, it was thought that the lack of accurate diagnostic tests did not have a major detrimental effect on clinical outcome. It was wrongly believed that if an outer enamel lesion was left untreated, it would have a high probability of progressing to dentine and early restoration of this shallow lesion might result in a smaller restoration which would destroy less tooth tissue.

However, this approach was challenged by Berman and Slack (1973) when they reported the results of a 3 year radiographic longitudinal study of posterior approximal surfaces in 11-year-old girls. They found that 50% of the enamel radiolucencies did not progress to dentine. This indicated that the previous assumptions of inevitable caries progression were incorrect and if the only criteria for restoring a tooth were based upon the presence of enamel radiolucencies, then probably 50% of the restorations were unnecessary.

The presence of suspected cavitation in an approximal tooth surface is an important factor in deciding whether or not to restore a tooth. Approximal enamel surface cavitation rates were reported as 34%, 66% and 87% of the surfaces which had radiolucencies in outer enamel, inner enamel and outer dentine of teeth examined in vitro (Marthaler and Germann 1970). Twelve years later a lower rate of approximal tooth

surface cavitation was reported of 14%, 20% and 52% for radiolucencies in outer enamel, inner enamel and outer dentine of teeth examined in vivo (Bille and Thylstrup 1982). A little caution is required in directly comparing the two sets of results since the methods were not identical. However, the magnitude of the differences in cavitation rates between the two studies is so large that it is difficult to believe that a significant reduction had not occurred during the time interval separating the investigations.

The combination of reduced caries prevalence, progression rates and late cavitation of tooth surfaces has lead to the development of preventive rather than treatment orientated philosophies coupled to a continual monitoring of dental health (Blinkhorn and Geddes 1987).

As disease patterns change it is to be expected that treatment patterns should also change and there is some evidence to support this. The results of examination of 12-year-old children in Somerset were compared with similar examinations conducted 6, 19 and 25 years previously (Anderson 1989). The average number of decayed missing filled teeth (DMFT) per child of 1.05 from the most recent examination was considerably lower than DMFTs of 5.36, 3.44 and 2.77 from the previous examinations of 25, 19 and 6 years previously. It is interesting to note that the major reduction over the last 6 years was in the average number of filled teeth per child.

Periodontal health has also improved significantly and there is a relatively low level of severe periodontal disease in adults of all

ages (Loe et al 1986; Burt 1988; Cutress 1988; Johnson et al 1988; Sheiham 1988). The following important conclusions were made by Burt (1988) that 1) it is no longer accepted that everybody is susceptible to serious generalised periodontitis, 2) generalised, destructive periodontitis is unusual among adult populations, even where oral hygiene is poor, gingivitis severe and professional treatment limited, 3) where oral hygiene is better, periodontitis is even more unusual though gingivitis is common.

This has important implications regarding the traditional role of dentists in preventing and treating periodontal disease. During 1981 to 1987, in England and Wales there was a 24% increase in the provision of periodontal treatments and a 21% decrease in the number of teeth filled in General Dental Practice (Dental Estimates Board 1987). Yet during this period epidemiologists have shown that the level of destructive periodontal disease was uncommon and reducing (Burt 1988; Cutress 1988; Sheiham 1988). It may well be that as Anderson (1989) indicated, although disease patterns may change, there can be a lag of several years before a profession is persuaded to adopt a modern philosophy and apply the principles in practice.

1.2 Disease distribution and clinical surveys

Cross-sectional surveys of populations have a major limitation in that single examinations, at a given point in time, cannot distinguish between past and present disease activity (Griffiths et al 1988). Mean values of past disease activity can be derived from cross

sectional-surveys to express disease experience for a group of people. However this fails to take into account the range or severity of disease which can be experienced by individuals in the population (Carlos et al 1986). It is important to determine if sub-groups exist in the population and their relative sizes. Disease progression can be measured by longitudinal studies which can discover population sub-groups. Loe et al (1986) discovered in their longitudinal study that a small sub-group exhibited rapid progression of loss of periodontal attachment (LPA). A deficiency of longitudinal studies using current clinical methods is they are only able retrospectively to detect high risk groups (Griffiths et al 1988). A high risk group is a collection of people who have a high probability of developing disease above a certain level. Ideally, predictive tests are required to identify high risk patients so that preventive regimes can be implemented, before destructive changes have occurred and their outcome closely monitored.

1.2.1 Caries distribution and diagnostic practises

In many industrialised countries, the distribution of caries experience in the population is highly skewed with a small number of people experiencing the majority of caries. In the County of Avon, it was found in 1986 that in 13- and 14-year-olds, 5% had more than half of the caries surfaces and 10% had three-quarters of the approximal lesions (Palmer and Pitter 1988). Similar observations have been made by other investigators (Grondahl et al 1977; Krasse 1985; Hugoson 1988b).

Despite these findings, that the majority of carious lesions are found in a minority of people, health care systems are usually designed with fixed and often inappropriate examination intervals (Herxheimer 1985). This does not encourage the clinician to search for people who suffer from an unusually high incidence or progression rate of disease.

There is some evidence to support the view that practitioners adopt simple screening philosophies partly due to the administrative systems they use. Jensen et al (1987) reviewed the examination intervals for bitewing radiographs performed by 25 practitioners on patients aged 16 years and above in New York. They found bitewings were taken routinely irrespective of age at alternate recall examinations (an average of 18 months between bitewings examinations and 8.4 months between recall examinations). Jensen et al (1987) concluded that "office routine, rather than the patients' dental status and anticipated radiographic yield, was the dominant factor that determined the frequency of bitewing exposure."

More disturbing are the findings by Mileman and Espelid (1988) who investigated practitioners radiographic prescribing habits for children. They performed a postal survey which revealed that 44%, 69%, 77% and 74% of Norwegian practitioners chose a 12-monthly bitewing examination interval for their patients aged 3-5 years, 6-12 years, 13-18 years and more than 18 years of age. Although only 44% of dentists selected the 12-monthly interval in the youngest age group, this was at least twice the number of dentists found in any of the

other time intervals. This suggests that most dentists in Norway have chosen a uniform radiographic time interval of 12 months to diagnose caries even though the incidence and progression rates are known not to be uniform but vary with age and other factors. The incidence reaches a peak 2-4 years after eruption and then declines rapidly (Carlos and Gittlesohn 1965). For the average child all the permanent teeth will have erupted by 13-years of age except for the third molars and the maximum incidence of caries will be passed by the age of 17 years. One would therefore expect a low caries incidence at 5-years of age and after 17-years of age. If the Norwegian practitioners were anticipating peaks in caries incidence between the study ages of 3-18 years and above, then it would be sensible for them to pick a variable and not a fixed radiographic interval of 12 months.

If this pattern of radiographic prescription indicates a lack of knowledge concerning variations in caries incidence and progression then it may be reasonable to assume that practitioners are also unaware of the skewed distribution of caries in a population and are not attempting to screen for high risk groups of patients.

1.2.2 Periodontal diseases distribution and diagnostic practises

World-wide there seems to be a prevalence of 7-15% of the adult dentate population who suffer severe destructive periodontal disease (Johnson et al 1988).

Loe et al (1986) demonstrated in a longitudinal study (conducted over

15 years) on Sri Lankan tea-estate labourers, that rapidly, moderately and non-progressive periodontal diseases were found in 8%, 81% and 11% of the population. This showed a spectrum of disease progression with only a comparatively small group showing substantial levels of periodontal breakdown. This was defined as gingival crevice depths of 6mm or more and a loss of periodontal attachment (LPA) of 4mm or more. A recent study conducted over 28 years on an American group of 165 adults showed that 59% had no LPA or an average loss of $\pm$ 1.0 mm per person; 13% 2.0 mm LPA; 3% 3.0 mm LPA and 1% 4.0 mm LPA or more (Ismail et al 1990). This work supports Loe's findings that substantial LPA is experienced only by a small percentage of an adult population

In a similar way to the high risk caries groups it would seem that in a population such groups also exist for the periodontal diseases. This will require practitioners to look actively for disease subgroups of high risk patients and again the little evidence which is available regarding their current diagnostic practises is again not encouraging.

Osman et al (1986) surveyed a group of 179 dental practitioners in the County of Avon in order to discover their reasons for taking radiographs. Only 8% of patients were radiographed for periodontal reasons in spite of the fact that the survey included patients of all ages.

The problem is not only confined to the United Kingdom. A group of 36 general practitioners in North Carolina were selected to study the

periodontal data collected in their patient records (McFall et al 1988). In each practice 80 records were selected for audit. Across the practices only 20.5% of records (over a 5 year period) recorded probing depths and presence of calculus, 13% gingival bleeding and 12% plaque. A periodontal diagnosis was recorded in only 16.3% of records. The authors concluded that the majority of patient records did not contain sufficient diagnostic information to describe a patient's periodontal health.

It would seem that if dentists are not collecting adequate data then there is very little hope of identifying high risk patients.

1.3 Diagnostic variability, treatment planning and disease prevalence.

Studies on diagnostic variability as indicated by treatment planning have been made on university teachers and practitioners. A Finnish study of 12 teachers who assessed the same radiographs of 10 students, diagnosed decayed surfaces with a range from 27-62 while the number indicated for treatment ranged from 31-72 (Rytomaa et al 1979). Mileman et al (1983) performed a similar study where 9 clinical teachers were presented with 12 pairs of bitewing radiographs representative of 15-year olds. The teachers as a group planned 19% overtreatment and 36% undertreatment.

Espelid (1986) performed a similar investigation of radiographic diagnosis and treatment decisions for approximal caries. Radiographs of 68 approximal surfaces were shown to 243 practitioners.

Restorations were proposed by the group for 15.6 ± 6.5 surfaces with a range of 0-65 surfaces. Fillings were proposed for 5% of sound surfaces and 25% of the dentists accounted for more than 80% of the treatment proposed for sound surfaces.

It is very disturbing to find such variation in decision making both among clinical teachers and practitioners. The radiographic diagnosis of approximal caries has been shown to be important in treatment decisions (Bille and Thylstrup 1982) and the addition of clinical variables increases the inter-examiner variation compared to in vitro situations (Merrett and Elderton 1984).

The variability of dentists' diagnostic decisions is of great importance since they serve as a weak basis for epidemiological surveys reporting caries prevalence (Espelid 1986) and for validating new diagnostic methods. As shown by Pitts (1988) and Griffiths et al (1988), the prevalence figures for both caries and periodontal diseases can be markedly altered by selecting different disease threshold criteria and applying it to the same data. By altering the disease threshold from initial caries lesions (D1) to caries of dentine (D3) [World Health Organization terminology, WHO 1979], Pitts (1988) demonstrated that the percentage of individuals considered free of fissure caries increased from 7% to 28%. Similarly, by selecting periodontal attachment levels of >= 1mm, >= 2mm, >= 3mm and >= 4mm, the prevalence of periodontal disease in 82 male subjects aged 17 years became 100%, 98%, 52% and 6% (Griffiths et al 1988). As shown in Table 1.1 (section 1.4) large variations in disease prevalence can

have a significant effect on diagnostic test performance and the choice of disease thresholds is important for evaluating tests.

1.4 The need for accurate predictive, diagnostic and monitoring tests

The weight of scientific evidence now seems to show that dentists and health workers will in the future be seeking to identify the minority of people who either will develop or have developed dental disease (Krasse 1985; Hugoson et al 1988a; Hugoson et al 1988b; Palmer and Pitter 1988; Loe et al 1986; Johnson et al 1988; Ismail et al 1990). If predictive tests can be developed then this will provide the earliest means of identifying the high risk groups in a population (Griffiths et 1988). Alternatively, or in combination with predictive tests, accurate tests are needed for diagnosing dental diseases at the earliest stages in their development so that preventive regimes can have time to be effective (Blinkhorn and Geddes 1988). Accurate diagnostic tests also have the potential for monitoring small changes of the tissues indicating destruction, repair or static lesions in individual patients. This is important in caries management because early carious lesions have the potential to remineralize (Kidd 1984). In the periodontal diseases the ability to detect a transition from an early lesion to an established lesion or vice versa (Page and Schroeder 1976, 1982 - section 2.5.3) could be used to decide if preventive regimes are succeeding and if a more interventional course has been selected, whether it is achieving its objectives.

Whether or not these tests will be used for screening subgroups of

populations will depend on a number of conditions being fufilled. Sheiham (1978) defined these conditions as "The dental disease should be an important health problem; there should be an effective and acceptable treatment available; the natural history should be understood and there should be an agreed policy on whom to treat."

However, designing accurate tests may be more difficult than common sense might indicate since the predictive value of a positive test varies with the prevalence of the disease - (predictive is used here to mean the percentage of all positive results that are true positives when applied to a population of healthy and diseased people). If a test for disease was shown to have a sensitivity of 95% (incidence of true positives found in patients known to have the disease) and a specificity of 95% (incidence of true negatives found in patients known to be disease free) then this might be expected to be a good test for detecting disease. With a disease prevalence of 50% this is indeed true with a predictive value of a positive test being 95.0 % (Galen and Gambino 1975). However with a low disease prevalence of 5% the predictive value falls to 50.0 %; with a 1% prevalence the predictive value is 16.1% and a prevalence of 0.1% reduces the predictive value to only 1.9% .

Since the incidence and prevalence of caries and the periodontal diseases has been shown to be decreasing, it becomes very important to know what proportion of the population is disease free since as it approaches 95%, previous tests with a high predictive value become no better than tossing a coin (Table 1.1).

Table 1.1 Effect of prevalence, sensitivity and specificity on predictive value of a positive test.

Prevalence %	Sensitivity and Specificity %	Predictive value of positive test %
0.1	95	1.9
0.1	90	0.9
5.0	95	50.0
15.0	95	77.0
15.0	90	61.4
15.0	85	50.0
15.0	80	41.4

For uncommon diseases, such as juvenile periodontitis, with an estimated prevalence of 0.1 - 0.5 % (Kronauer et al 1986; Bial and Mellonig 1987), the predictive value of a single positive test result is approximately 2% even with a sensitivity and specificity of 95%. Screening populations for diseases with such a low prevalence using tests producing large numbers of false positives are hard to justify in purely financial terms.

Tests exhibiting a sensitivity and specificity of 95% applied to populations with a disease prevalence of about 15% will achieve a positive predictive value of 77%. However if the sensitivity and specificity falls to 85% the predictive value falls to 50%. Since it

has been suggested that the prevalence of advanced LPA (>= 6mm) occurs in 10% or less of a population (Papapanou et al 1988; Ismail et al 1990), the performance of a test becomes critical if invalid results are to be prevented.

It would seem to be very important to evaluate the performance of existing diagnostic methods for detecting and monitoring caries and periodontal diseases since they are the key to the development and testing of hypotheses for disease activity, preventive regimes and treatment philosophies.

1.5 Aims of thesis

This chapter has introduced a number of themes including the reduction in the prevalence of dental diseases, the existence of small groups of people who seem to be at high risk of developing severe dental disease, the difficulty that dentists have in accurately diagnosing disease, that prevalence levels will alter with different diagnostic thresholds and diagnostic test performance will change with variations of disease prevalence. These topics examined individually are of interest but viewed collectively they reveal a critical need for the dental profession to be able to predict and identify high risk patients, detect early disease, accurately monitor disease and its response to preventive regimes and treatment.

The aims of this thesis are :-

1) to review existing prognostic methods for identifying high risk

patients before they develop caries and periodontal diseases.

2) to review existing diagnostic methods for caries and periodontal diseases.

3) to select the best diagnostic method from those available based on criteria of validity, reliability and ease of use.

4) by experiment to investigate those factors which affect the validity and reliability of the test.

5) design experiments to improve the reliability and suitability of the test for general clinical use.

6) make recommendations for further work.

In the next chapter we shall consider the pathological changes which occur in dental caries and the periodontal diseases together with the implications for designing prognostic and diagnostic tests.

Chapter2 The relationship between dental anatomy, disease changes and diagnostic tests.

2.1 Introduction

In this chapter we shall consider the anatomy of the regions of interest; describe how they alter in response to disease; discuss test performance and the implications of this for evaluating tests.

2.2 Dental anatomy and pathological changes

Caries will be discussed first followed by periodontal disease.

2.3 Caries

Teeth are composed of four principal tissues; enamel, dentine, pulp and cementum.

Dental caries is a softening of hard tissue due initially to loss of calcium ions from enamel and if the carious process continues, eventually dentine and pulp will be affected. The majority of caries now occurs in the occlusal fissures of posterior teeth (Moller 1987) although there is some preliminary evidence of an adult high risk group for root surface caries (Beck 1990).

2.3.1 Aetiology of caries

Caries has been shown to require the presence of bacterial plaque on teeth (Miller 1883; Orland et al 1954) and refined carbohydrates (Gustaffson et al 1954) to produce hydrogen ions which removes calcium from enamel hydroxyapatite crystals. The principal bacterium implicated in the carious process is Streptococcus mutans although some strains of Lactobacillus and other organisms can produce acid in an oral environment (Gibbons and van Houte 1975). Caries is a multifactorial disease since the composition of the bacterial plaque, length and frequency of exposure of tooth surface to acid production (Stephan 1940) and presence of free fluoride ions (Dean 1938,1939) all contribute to a dynamic equilibrium which can remove or replace calcium ions (Silverstone 1984; Kidd 1983; Joyston-Bechal and Kidd 1986; Kidd and Joyston-Bechal 1987).

2.3.2 Histopathology of the white spot lesion

Caries is a slow process (Pitts 1983a) which in part explains the complicated structure of the early enamel or "white spot" lesion. It is composed of 4 regions or zones based upon its histological appearance when ground sections are examined with a polarising light microscope. Using a clearing agent, such as quinoline which has the same refractive index as enamel, different refractions can be seen compared to water (Joyston-Bechal and Kidd 1986).

Zone 1 is a translucent region, which is not always present and lies

at the deep advancing front of the lesion. Normal enamel has a pore volume (spaces) of about 0.1% whereas the translucent zone has a pore volume of 1.0%, due to demineralization, which accounts for its visibility.

Zone 2 or the dark zone is just superficial to the translucent zone. The dark zone has a pore volume of 2-4% and may represent an area of remineralization. Clinically arrested lesions have histologically wide, well developed dark zones (Kidd 1983).

Zone 3 or the body of the lesion comprises the largest proportion of the carious enamel in the small lesion. It is superficial to the dark zone and deep to the surface layer. The pore volume is variable with only 5% at the periphery but increasing to 25% or more in the centre.

Zone 4 or the surface zone is the most superficial layer which appears to be unaffected although it has an increased pore volume of 1%.

If a white spot lesion continues to grow, eventually the surface layer will break up and a cavity forms. However, there are no definite criteria such as lesion size, age or activity which can be used to predict exactly when cavitation will occur.

It is believed that the surface layer is related to the presence of an overlying layer of plaque which acts as a diffusion barrier trapping calcium, phosphate and fluoride ions released by surface dissolution. This in turn is thought to favour remineralization of the surface

layer (Kidd and Joyston-Bechal 1987).

2.3.3 Morphology of caries

In smooth surface lesions, approximal and buccal surfaces, the lesion is often cone shaped with the apex of the cone pointing towards the amelodentinal junction (ADJ). However, the shape is variable. Zamir et al (1976) reported 66% of lesions being triangular shaped, 16% diffuse and 18% of unclassified shape.

Early smooth surface caries and fissure caries are histologically very similar with the same zonal structure. However, whereas smooth surface caries tends to form one discrete lesion, fissure caries tends to form two lesions on either side of the fissure which only coalesce when the lesions extend to involve the base of the fissure. Unlike smooth surface lesions, fissure caries has a broader base of deminerlization at the ADJ than at the surface. This leads to undermining of sound enamel and often extensive dentinal involvement occurs (Kidd and Joyston-Bechal 1987).

2.3.4 Tooth response to caries

When the advancing front of the lesion reaches the ADJ, acids and other chemical irritants stimulate the pulp dentine complex. This may result in tubular sclerosis of dentine caused by the active deposition of mineral in the dentinal tubules producing a Translucent Zone of dentine. Unlike the translucent zone in enamel which is

hypomineralised, this is hypermineralised. In addition reactionary dentine may form at the dentine-pulp interface (Kidd and Joyston-Bechal 1987).

It is believed that the presence and integrity of the enamel surface layer is critical for the potential of lesion remineralization (Konig 1984). In vitro experiments have shown that natural white spot lesions can remineralize using fluoridated toothpaste slurries (Joyston-Bechal and Kidd 1986, Damato et al 1990). Breakdown of the enamel surface would allow bacteria easier access to dentine with an increased risk of lesion progression. However, there is very little published work on the sequence of events which follow early surface breakdown since clinically this is difficult to detect.

2.3.5 Requirements of an ideal caries test

It has been shown from the above that histogical and pathological changes of carious lesions are well known although not all the processes have been elucidated. The high risk sites of the teeth are the pits, fissures and approximal contact areas. The rate of caries progression for the average patient is slow with about 3-4 years required to penetrate to the ADJ assuming the lesion does not arrest or remineralize and 5-6 years if outer enamel lesions are included (Pitts 1983a).

From a consideration of these facts it is possible to define what is required from an ideal test/s for caries:-

1 It should predict the initial onset of disease allowing time for preventive measures.

2 It should be capable of detecting the carious process before the enamel surface cavitates and preferrably while it is still confined to enamel.

3 Enamel surface breakdown, both microscopic and macroscopic should be detectable since this can affect enamel remineralization (Konig 1984).

4 It should be able to detect progression, remineralization or stasis of the lesion.

5 The thickness of the enamel cap in the approximal contact region of the premolars and molars is between 1.0 mm to 1.2 mm. Assuming that caries progresses at a linear rate (it probably does not) and that four years are required for a lesion to pass through the full thickness of enamel, then in one year the lesion will progress one quarter of enamel thickness or 0.25 mm to 0.30 mm. If a 0.30 mm change in depth of the lesion is to be detected with a 95 % reliability then the Standard Deviation (SD) should be about half this value or 0.15 mm since 1.96 x SD= 95 % confidence level for a sample population.

It would seem that if the above reasoning is correct, an annual clinical examination for detecting early caries or change in lesion status (individual patient monitoring) will require a diagnostic method with an accuracy of SD 0.15 mm and a measuring interval of probably 0.05 mm to 0.7 mm.

(Although these figures were derived from a consideration of the approximal regions they should also be appropriate for fissure caries.)

6 Since carious lesions are irregular in shape, it would be advantageous to be able to detect 3 Dimensional changes.

7 The diagnostic method should offer no significant hazard to the patient and should be repeated as often as clinically indicated within the limits of patient tolerance and cost.

8 The presence or absence of living bacteria within the body of the lesion should be detectable together with an estimate of their activity.

9 The extent and severity of carious lesions should be reported for each patient rather than just a single value summarising the extent which is the limitation of the current DMFT/S system (Carlos et al 1986).

2.4 Periodontal diseases

The periodontal diseases are associated with bacterial plaque and are characterised by gingivitis which is usually reversible (Loe et al 1965), but may proceed to destruction of the periodontal ligament and supporting alveolar bone. If the loss of attachment is severe, the tooth will become mobile and may be lost.

2.4.1 Anatomy of the periodontium

The periodontium is composed of four tissues: the gingiva, the

periodontal ligament, the root cementum and the alveolar bone.

The gingival soft tissue is closely adapted to the roots of teeth and covers the alveolar bone proper which is an extension of the alveolar process. The most coronal portion of the gingiva is not firmly bound to bone and is called the free gingiva; this has a rounded edge at its margin, hence the name free gingival margin (FGM). A thin blunt probe can be gently inserted between the FGM and the crown of the tooth to enter a potential space called the gingival pocket or crevice.

Between the alveolar bone and the root cementum are collagen fibres, blood vessels, nerves and lymphatics which collectively are called the periodontal ligament which fills the periodontal ligament space (PLS). A cribriform plate of compact bone lines the bony wall of the PLS and coronally forms the alveolar crest margin. The plate is connected with the buccal and lingual/palatal cortical plates of the jaws.

Deep to the covering layers of cortical bone is the cancellous bone containing a supporting framework of bony trabecular plates and rods with the remaining spaces filled with vascular tissue.

2.4.2 Aetiology of the periodontal diseases

The periodontal diseases are characterised by infection and inflammation of the periodontal tissues which is thought to originate as a microbial infection of the gingival sulcus.

The involvement of bacterial plaque has been shown by a short-term experiment where volunteers abstained from toothbrushing for a few days. During this time plaque collected and clinical gingivitis developed but when normal hygiene measures were reintroduced, the gingivitis resolved showing that gingival inflammatory changes may be reversed if plaque formation is prevented (Loe et al 1965).

At some stage, and for reasons as yet unknown, the inflammatory changes cause destruction of periodontal collagen fibres with or without accompanying destruction of alveolar bone. Differences in bacterial composition have been demonstrated between gingivitis and periodontitis (Newman et al 1976). Cross-sectional studies have indicated that the subgingival microflora in gingivitis is composed mainly of Gram-positive Streptococcus sanguis, Strep. mitis and Actinomyces viscosus (Slots 1979). In patients suffering from periodontitis, the subgingival flora have shown higher proportions of Gram-negative bacteria, such as Actinobacillus actinomycetomcomitans, Bacteroides gingivalis and B. intermedius (Slots and Genco 1984; Slots 1986). Traditionally destructive periodontal disease has been thought to be caused primarily by a single or a very few types of organism. However, there is now some evidence to suggest that different infections can occur at the same time in a person's mouth and that different organisms over time can be responsible at a single site for causing destruction (Socransky et al 1987). Results from recent work by Christersson et al (1989) has led them to propose two hypotheses for the pathogenesis of periodontitis. The first is a gingivitis-dependent hypothesis which suggests that inflammatory

changes caused by gingivitis facilitate subgingival colonization by periodontal pathogens such as B. gingivalis. The second, or gingivitis-independent hypothesis proposes that gingivitis and periodontitis are distinct entities and that clinical methods for preventing or treating gingivitis may be inadequate to prevent periodontitis.

2.4.3 Clinical signs and histopathology of periodontal lesions

Biopsies from clinically healthy areas of the periodontium have revealed that a small infiltrate of inflammatory cells is always present in the coronal portion of the gingiva adjacent to the junctional epithelium (Page and Schroeder 1976). In the clinically healthy periodontium it has been suggested that the presence of small numbers of inflammatory cells is the "normal" situation indicating the body is successfully coping with a continuing bacterial challenge from the oral cavity (Wennstrom 1988).

As the degree of inflammation increases, clinical signs of gingivitis may appear with enlarged papillae due to oedema, redness, an apparent increase in probing depth of the gingival sulcus and even bleeding from gentle probing may occur. If the inflammatory changes extend to produce destruction of collagen fibres inserted into the root cementum, the gingivitis becomes a periodontitis (Listgarten 1986).

Page and Schroeder (1976, 1982) have suggested a four stage histopathologic classification of periodontal disease:-

The initial lesion is characterized by vascular dilatation and increased permeability to fluid and cells from the blood.

The early lesion is identified by a lymphocyte-rich infiltrate which develops adjacent to the junctional epithelium and the local collagenous fibre network is destroyed.

The established lesion is a further extension of the early lesion with plasma cells becoming the dominant cell of the inflammatory infiltrate. Further collagen destruction and epithelial proliferation into the infiltrated connective tissue are also features of this stage.

The advanced lesion is typical of periodontitis and includes all the features of the established lesion together with bone destruction, pocket formation and further apical migration of the junctional epithelium.

The amount of loss of periodontal attachment is critical since if it is severe and progressive, the retention of the tooth or teeth affected may be such that a tooth exfoliates or is extracted.

2.4.4 Gingival Crevicular Fluid

From the gingival sulcus a gingival crevicular fluid (GCF) can be collected using a filter paper. The GCF contains various immunological and chemical components which have been found to vary with clinical conditions. Cimassoni and Giannopoulou (1988) reported on an experimental gingivitis in man where 8 sites from 4 patients were sampled before and after a 4 day period of plaque accumulation. The

average GCF flow doubled after 4 days of no brushing but in some sites there was no increase of GCF flow. The number of polymorphonuclear leucocytes trebled at all sites.

In other investigations Lamster et al (1987) demonstrated a positive correlation between increasing probing depth and GCF volume while Villela et al (1987) showed a strong correlation between GCF collagenase and probing depth. These findings have led researchers to look for other changes in GCF linked to inflammation (sections 2.5.1, 3.3.8).

2.4.5 Potential for lesion healing

Periodontal lesions do not necessarily progress and lesions can remain stable over long periods of time or reverse spontaneously from an established lesion to an early lesion (Listgarten et al 1978).

2.4.6 Classification of the periodontal diseases

Numerous classifications of the periodontal diseases exist (Grant et al 1988) probably indicating that similar to caries, the periodontal diseases result from multi-factorial interactions between the host and their environment.

A relatively simple classification of periodontal diseases into six main disease groups has been suggested by Suzuki (1988). He proposed that the finding of certain signs and symptoms would lead to the

diagnosis of either Adult periodontitis, Rapidly Progressive periodontitis (types A or B), Juvenile periodontitis, Post-Juvenile periodontitis or Prepubertal periodontitis. This was based on a consideration of age, sex, local or generalized distribution of the lesions, association with tooth materials, caries rate, neutrophil chemotaxis, autologous mixed lymphocyte response and genetic factors.

2.4.7 Theories and rates of periodontal disease progression

Two main theories of periodontal disease progression have been proposed. Prior to the early 1980s, data from cross sectional and longitudinal studies of chronic adult periodontitis had led to a population model of slow continuous LPA of about 0.1 mm per year (Axelson and Lindhe 1978; Becker et al 1979). However, Goodson et al (1982) challenged the slow continuous progression theory with one of intermittent bursts of destructive activity, the so-called Burst Theory, which could be followed by partial or complete recovery. They suggested that the majority of sites would not change and those that did would alter over short periods of days or weeks. This was supported by a study on 22 untreated subjects which showed that in 1 year, 82.8% of sites did not significantly alter (Goodson et al 1982). Further supporting evidence was supplied by the same group 2 years later when they reported that only 12% of sites in 64 patients examined over a 6 year period had more than 2mm LPA (Socransky et al 1984). In addition they found that only 40% of the sites which suffered LPA in the first 3 years of the study, suffered further LPA in the second 3 years.

The burst theory has gained widespread acceptance by periodontologists as a likely model for explaining periodontal disease progression. Johnson et al (1988) drew attention to other diseases, such as Rheumatoid arthritis, which are chronic inflammatory diseases which progress by series of bursts of acute activity followed by periods of remission.

However, severe reservations have been expressed by Birkedal-Hansen et al (1988) regarding the Forsyth group's statistical analysis of their data and the accuracy of the LPA measurements which led them to formulate the burst hypothesis (Goodson et al 1982). Their criticisms revolved around the inaccuracy of probing techniques (Listgarten 1980) and the use of 2 new analytical techniques, designed to discriminate between disease "active" and "inactive" sites (Haffajee et al 1983b). The concluding remarks by Birkedal-Hansen et al (1988) were "Probing attachment level changes, therefore, should not be accepted uncritically as absolute evidence of loss (or gain) of functional attachment. If a 1-2 mm probing attachment level change accounted for by inflammation alone is added to a 2-3mm apparent loss accounted for by measurement error it is possible to envision substantial probing attachment loss without any true progression of disease." These comments have been quoted in full since they seem to sum up very well the current dilemma in dental diagnosis which is the need for accurate methods to test disease models.

2.4.8 Requirements of an ideal periodontal diseases test

The periodontal diseases are a group of inflammatory disorders which share a common set of histopathological changes and are associated with the presence of microbial plaque (Loe et al 1965). Adult chronic periodontitis is thought to be associated with bursts of destructive activity and long periods of inactivity at individual sites (Goodson et al 1982; Socransky et at 1984). The 5 other classifications of periodontitis share the same histopathological changes but have variations in age of onset, rates of progression and other features (section 2.4.6).

From a consideration of these facts it is possible to define what is required from an ideal prognostic or diagnostic indicator for periodontal diseases:-

1 Predict the onset of initial disease.

2 Detect the presence or absence of disease.

3 Predict progression of the disease.

4 Detection of a change from gingivitis to an initial periodontal lesion since diagnosis of gingivitis alone is not a diagnosis of periodontal destruction (Page 1986; Johnson et al 1988; Wennstrom 1988).

5 Distinction between an active disease site and an inactive one (Johnson et al 1988). This will probably be important for the small percentage of patients who have rapidly progressive periodontal destruction since the first evidence of therapeutic success would

presumably be the conversion of active sites to inactive ones.

6 Ability to distinguish between collagen breakdown and bone resorption over and above normal turnover.

7 Structural details of alveolar bone. Qualitative and quantitative chemical tests concerning bone remodelling will certainly be important for diagnosing and monitoring periodontal diseases. However, the ability to visualize alveolar bone will be an essential confirmation that remodelling is preserving the skeletal support for the periodontal tissues.

8 Provide objective data.

The current controversy regarding whether bone is lost continuosly or in bursts will not be settled until small accurate measurements can be made. It is suggested that crestal bone measurements of SD 0.15mm are needed. Even though this seems to be a very small distance, it should be remembered that clinically readings will have to be thresholded at 0.3 mm (2 SD) to reach the 95% confidence level. If bone is resorbing at a constant rate of 0.2 mm per year, it will require 2 years to lose 0.4 mm which is just outside the 95% confidence level providing detection of crestal height. Of course a burst of 0.4 mm of bone resorption could occur in a few days which would be indistinguishable from slow continuous loss over the same time period. In order to identify the rate of loss, short time interval as well as accurate measurements are required.

As further work is performed, to clarify the interactions between plaque and the periodontal tissues, new markers for disease will be

discovered which will be used to diagnose the periodontal diseases (Johnson et al 1988). [The term "marker" in this thesis is used to mean an indicator of future or current disease].

2.5 Predictive and diagnostic tests

Disease tests can be broadly divided into predictors of future disease and diagnostic of current or past disease.

2.5.1 Predictive tests

A predictive test is one which seeks to detect a single marker or group of markers which if present, indicate that an individual has a certain probability in the future of developing a disease. If this was at a healthy site then this would be a marker for initial disease. A marker which predicted disease at a site which had already experienced one or more attacks of disease would be a predictor of disease progression. From this classification it is logical that markers will be linked to factors involved in the aetiology of the disease or to the initiating agents, their products or the host response. Both caries and the periodontal diseases have an intimate relationship with bacterial plaque (sections 2.3.1, 2.4.2) and a great deal of research effort is currently being spent on evaluating certain bacterial strains such as Strep. mutans and Lactobacilli as potential predictive markers for caries (Klock et al 1989; Sullivan et al 1989; Alaluusua et al 1990). In the search for periodontal predictive markers, the peripheral blood, saliva, GCF, subgingival bacterial

plaque and periodontal tissues are being investigated (Fine and Mandel 1986; Johnson et al 1988). The predictive markers will be reviewed in chapter 3.

The usefulness of predictive tests should be seen in relation to the length of warning time they can provide compared to the progression activity of a given disease and the anticipated test sampling intervals.

From Table 2.1, produced by the author, it can be seen that the preventive value of a predictive test is not simply the maximum warning period the test can provide. If one accepts that the burst theory is valid for the periodontal diseases (section 2.4.7), then the combination of predictive warning period and examination interval must be such that a short lived burst is unlikely to occur without an effective warning period. This seems to indicate a requirement of a test with a minimum predictive warning of 12 months for 6-monthly examinations or 18 months for 12-monthly examinations.

The demands of caries predictive tests are less rigorous due to the slow progression rates of the disease (Pitts 1983a) and the potential for remineralization (Joyston-Bechal and Kidd 1986 - section 2.3.4). Relatively short predictive periods of 6 months with a 24-month examination interval are at worst likely to reveal early enamel lesions of 18 months duration, which are unlikely to have cavitated due to slow progression (Pitts 1983a; Bille and Thylstrup 1982). Caries predictive tests with 12 months warning used at 12 or 24-month

Table 2.1 Relationship between examination intervals, predictive warning period of a test and its preventive value to dental disease.

Exam interval	Max predictive period of test	Effective warning Max, Min	Preventive value Perio	Caries
months	months	months		
24	18	<=18, -6	-	+
18	18	<=18, 0 *	-	+
12	18	<=18, 6	+	+
6	18	<=18, 12	+	+
24	12	<=12,-12	-	+
18	12	<=12, -6	-	+
12	12	<=12, 0 *	-	+
6	12	<=12, 6	+	+
24	6	<= 6,-18	-	+
18	6	<= 6,-12	-	+
12	6	<= 6, -6	-	+
6	6	<= 6, 0 *	-	+

Notes:

* even though it would appear that this combination of examination interval and predictive warning period is very likely to provide in most cases some advance warning of disease, for a few patients a burst of destructive periodontal disease will have occurred with little or no warning. A negative minimum effective warning value means a lack of warning.

intervals should provide ample time for implementing preventive regimes.

In addition to the effective warning provided by predictive tests, their cost should be considered which should include chairside professional time. It may be that unless ancilliary workers can be utilized or patient self-assessment at home performed, the cost of using technically successful predictors may be prohibitive on a population-wide basis. Even if patients could be persuaded to perform self-assessment, this would be an unrealistic goal unless simple tests could be designed which would rule out multiple site plaque sampling. These topics will be considered further in chapter 3.

2.5.2 Diagnostic tests

Diagnostic tests should be able to detect changes which are due to current active disease sites. Unfortunately it is possible to use tests which detect evidence of past disease but are unable to distinguish between active and inactive sites (Griffiths et al 1988). Cross sectional and longitudinal radiographic and LPA surveys only reveal changes from past disease. However, longitudinal surveys do provide evidence of disease progression over the investigation period. This can be used to determine if an individual has suffered greater disease change than the majority of their cohort which has been called an assessment of "severe disease for age" (Loe et al 1986; Griffiths et al 1988).

2.5.3 Collection of data

When evaluating tests many factors need to be considered besides efficiency or accuracy:-

2.5.3.1 Unit of sample

Sampling can occur at various levels such as site, subject or group. At the site level in periodontal studies this could be 6 attachment level measurements per tooth and up to 5 surfaces per tooth for caries. The problem in using site level statistics for evaluating disease is the potential lack of independence between sites in the same subject (Sterne et al 1990). However, the condensation of many measurements into a single value for allocating people to groups does overcome the lack of sample independence but carries the penalty of losing information. This occurs when the prevalence of periodontal disease is defined as the proportion of subjects with at least one site where the LPA exceeds a threshold value. The difficulty of selecting the most appropriate sample unit to best represent disease presence and activity should be borne in mind when designing surveys or comparing results between different survey methods.

2.5.3.2 Combination testing

Scocransky et al (1987) suggested that multiple tests will be required to identify the agents responsible for destructive periodontal disease. However, tests performed serially behave differently to the

same tests used in parallel on the same data. Parallel testing results in the highest sensitivity but the lowest specificity whereas series testing results in the lowest sensitivity but highest specificity (Galen and Gambino 1975).

2.5.3.3 Practical considerations

Disease markers should ideally appear well in advance of pathology to achieve useful prediction, be stable over time and highly specific for the disease of interest. Minimal skill and time should be required to identify and measure the markers in order to reduce the costs of the test. The data acquired should be objective and amenable to computational analysis (Griffiths et 1988).

2.6 Test definitions

Since there is occaisionally confusion within the literature regarding terminology concerning diagnostic tests and performance, the following definitions and examples are provided.

2.6.1 Precision

Precision describes the scatter of measurements from the true unbiased value of what is being measured (Bourke et al 1988).

2.6.2 Accuracy

An accurate measurement is one which varies very little (is very precise) from the true measurement (Bourke et al 1988).

2.6.3 Validity

Validity describes how well our measurements represent the characteristics we wish to measure. If we wish to measure the LPA and we directly measure from the cemento-enamel junction (CEJ) to the most coronal fibrous attachment then the validity will be very high. However, there may be considerable variation in our measurements which will affect their reliability.

2.6.4 Reliabilty

Reliabiblity is an indication of the stability of the data obtained from a method for measuring disease when the measurements are made more than once, assuming no disease change. Equivalency indicates the consistency between examiners and/or measurements performed at the same time.

Reliability can be reduced by a lack of constancy due to variations such as lighting and examiner position.

A lack of precision will reduce the reliability of a measurement, for example variation of probing force will produce different values of

probing depth in the same pocket.

Errors due to variation of instruments used, such as periodontal probe diameters, is called a lack of congruency.

2.6.5 Relationship between validity and reliability

Validity and reliability are interdependent concepts. "The internal validity describes the validity of our variable as an expression of the characteristic we want to observe, the reliability describes the precision of our measurements and the external validity expresses the total validity of our data" (Gjermo and Rise 1988).

2.6.6 Sensitivity and specificity

The sensitivity of a test measures its ability to detect true cases (true positives or TP) and is defined by the number of true positives as a percentage of the total with the disease. The positive results obtained from individuals without the disease are called false positives or FP.

The specificity of a test is its ability to detect disease-free individuals and is defined as the number of true negatives (TN) divided by the total without the disease. Negative results produced by the test on individuals with the disease are called false negatives or FN.

2.6.7 Predictive value of a test

The predictive value of a positive test (PV+) is the proportion of true positives compared to the sum of true positives and false positives expressed as a percentage ie

$$\frac{TP}{TP + FP} \times 100$$

The predictive value of a negative test result (PV-) is the proportion of true negatives compared to the sum of true negatives and false negatives expressed as a percentage ie

$$\frac{TN}{TN + FN} \times 100$$

2.6.8 Efficiency of a test

The efficiency (or accuracy) of a test is the proportion of true positive and true negative results compared to the number of subjects in the study (n), expressed as a percentage ie

$$\frac{TP + TN}{n} \times 100$$

2.7 Summary

This chapter has described the relationship between dental anatomy and the changes observed with dental caries and the periodontal diseases.

It is important to understand these changes since they indicate disease. It is the ability of a test to accurately predict or measure these changes which will decide if it will be a valid and reliable test.

An indication of some of the critical stages in the development and activity of the diseases has been described, within the limitations of our current knowledge. An ideal test should be able to detect and report these stages.

A discussion of some of the potential limitations of predictive tests has been made together with a brief list of diagnostic test performance indicators.

In the next chapter there is a review of the literature concerning existing prognostic and diagnostic tests for caries and periodontal diseases which will be discussed using the background information of this chapter.

Chapter3 Review of the literature relating to predictive and diagnostic tests for caries and the periodontal diseases.

3.1 Predictive tests

As described previously (section 2.5.1) predictive tests seek to identify markers of future disease to find high risk individuals or groups of people with the aim of implementing preventive regimes. The cost of prevention programmes could be greatly reduced and their efficiency increased if the practitioner or health administrator could identify in advance high disease risk subjects (Hunter et al 1988; van Palenstein Helderman et al 1989).

3.2.1 Caries predictors

The use of a number of different potential markers has been investigated either singly or in combination for predicting caries activity. These have included:-

i) initial caries prevalence scores in primary or permanent teeth (van Palenstein Helderman et al 1989; Seppa et al 1989; Alaluusua et al 1990).

ii) initial prevalence scores and age (Seppa et al 1988).

iii) initial prevalence scores and obesity (Tuomi 1989).

iv) salivary lactobacillus counts (Crossner 1981; Pienihakkinen et al 1987; Kingman et al 1988; Block et al 1989; Sullivan et al 1989).

v) initial prevalence scores and lactobacillus counts (Alaluusua et

al 1990).

vi) salivary lactobacillus and yeast counts (Pienihakkinen et al 1987).

vii) salivary Streptococcus mutans counts (Kingman et al 1988; Klock et al 1989; Sullivan et al 1989).

viii) salivary S.mutans and lactobacillus counts (Holbrook et al 1989).

ix) salivary S.mutans and initial caries prevalence (Alaluusua et al 1990).

The bacterial tests usually take the form of collecting stimulated saliva, from chewing a block of wax, and pouring it over a microscope slide covered in a nutrient medium. The slide is then incubated in an oven for 4 days or at room temperature for 7 days and the number of colonies compared by eye against a reference chart (Alaluusua et al 1984). Lactobacillus counts in saliva represent one of the earliest and most widely used tests for caries activity (Larmas 1975). It is believed that lactobacillus counts may have a special value in assessing sugar intake (Hunter et al 1988; Abrams et al 1989). Both S.mutans and lactobacillus dip slide methods are available for chairside use (Dentocult, Rexodent Ltd, Southall).

Vanderas (1986) in an extensive review of caries predictors found that it was difficult to make a direct comparison between the results of studies, since there was no standard experimental protocol. In this review of recent papers a similar problem was found (Table 3.1).

Table 3.1 A summary of 11 recent studies for caries prediction.

Authors	Sample size n	Age yrs	Study yrs	DMF mean	PV+ %	PV- %	Accuracy %	Test
Holbrook et al 1989	158	4	x	3.3(S)	49	89	68	S.mut & lact
Sullivan et al 1989	87	5-7	2	3.2(S)				S.mut (6%),lact (3%) varnce
Pienhakk et al 1987	298	6-11	3				57-77	Lact, yeasts
Kingman et al 1988	541	10-15	1.4	4.6(S)	31(39)	81(84)		S.mut (Lact)
Seppa, Hausen 1988	124	11-13	5	17.4(S)	47	80	70	DMFS & Age
Crossner 1981	115	14	1.2	10.7(S)	85	80		Lact
Klock et al 1989	100	14	1	4.9(T)	31(46)	61(70)		S.mut (Lact)
Alaluusu et al 1990	122	12-17	3	6.7(S)	43(56)			DFS & S.mut,(DFS & Lact)
					60			DFS alone
Seppa et al 1989	512	6-13	7	10.2(S)	57(61)	85(84)	78(81)	DMFS at age 6,(9) years
Palenst et al 1989	286	7-11	4	0.9(S)		60	83	DMFS fissures age 7 years
Tuomi 1989	516	5-13	8				72(80)	dmfs (DMFS)+obesity age 5,(8)years

Notes: x= cross sectional study; (S)= surface; (T)= teeth; S.mut= Streptococcus mutans;
Lact= Lactobacillus; varnce= variance.

Most of the recent studies made a clinical examination with a mirror and probe together with bitewing radiographs, although the radiographic criteria for diagnosing caries varied from study to study. Alaluusua et al (1990) followed Moller's (1966) scoring method and excluded incipient occlusal lesions, visible decalcified enamel spots and approximal radiolucencies less than 2/3 through enamel (Moller's Criterion 1). The exclusion of this initial caries from the prevalence score was common in the studies.

It would be reasonable to expect that in increasing the disease threshold by excluding initial caries, a significant change in prevalence would result (Pitts and Fyffe 1988). In turn this should affect the positive predictive values (PV+) and negative predictive values (PV-) of a test. When Seppa and Hausen (1988) calculated the predictive values with and without initial caries values being included in the DMFS scores, surprisingly the PV+ values increased by only 2% from 45-47% and the PV- values by 1% from 79-80%. Unfortunately the change in DMFS scores was not provided.

It is difficult to explain the very small change in predictive values caused by altering the diagnostic threshold. Perhaps it is because initial lesions, defined by Seppa and Hausen (1988) as intact white spot lesions with radiolucencies less than 1/4 enamel thickness, are unlikely to progress in these children since they had life-long exposure to fluoridated drinking water (1.2 ppm). If this was true, it would explain the lack of sensitivity of the predictive test to early caries and it raises an interesting possibility. As Carlos et

al (1986) commented, knowing the prevalence of a disease is of limited value without measuring its severity. The studies of caries predictions based on initial prevalence scores all use the DMFS/T system which provides no idea of severity. It would be interesting to see if initial caries severity scores for each lesion would have a greater predictive value than the conventional DMFS/T index. Although a severity index based on the tooth surface has been used (Grainger Severity Index) it is in reality a modified DMFS index and only provided a slight increase in correlation coefficient to 0.41 (Hunter et al 1988). A severity index could be based on radiolucencies using 1/2 thicknesses of enamel and dentine with an appropriate weighting for deeper lesions. Pitts (1985) has proposed a similar scoring system but based upon observed progression between serial radiographs rather than for predicting caries incidence from an initial examination.

Another possible reason for the lack of predictive power using initial DMF scores may be the arbitrary selection of the high risk criteria. Seppa and Hausen (1988) chose "about" 30% of the children with the highest caries scores to be the high risk group while in a later study Seppa et al (1989) selected the upper quartile of caries experience in 13-year-olds as the cut off point between high and low risk groups for the "real" caries developed. There would seem to be a need for a more objective way to decide what is a high risk group.

Comparisons between studies with similar age groups but widely differing initial caries prevalence may not be wise. Seppa et al

(1988) studied children aged 11-13-years-old with a baseline DMFS of 17.4 whereas Kingman et al (1988) observed 10-15-year-old children with a baseline DMFS of 4.61. Often predictive studies are performed in conjunction with preventive regimes which doubtless have an effect on caries incidence and progression rates which in turn would interfere with caries prediction tests.

The manner of test reporting was found to be inconsistent with few researchers quoting PV+, PV- and diagnostic efficiency (accuracy). Nevertheless, it can be seen from Table 3.1 that all the reported predictive tests have a high PV- compared to the PV+. This is not surprising since tests used to detect low prevalence diseases are liable to provide a higher proportion of false positives than false negatives.

The majority of the tests fall into the PV+ range of 30-61% indicating that they are very unreliable indicators for predicting future disease. However the PV- range of 60-89% was much higher with the majority about 80%.

It would seem that the existing caries prediction tests could usefully be used to screen children into a low risk group who could be excluded from preventive regimes. The remainder could form a "default" high risk group.

Although microbial markers have been included in a high proportion of studies, when their performance is examined alone (Kingman et al 1988;

Holbrook et al 1989; Klock et al 1989) their PV+ is usually less than just using initial prevalence scores (Seppa et al 1989; Alaluusua et al 1990). Sullivan et al (1989) demonstrated that only 6% and 3% of the total variance was explained by S.mutans and lactobacilli when predicting caries supporting their view that salivary microbial tests are not strong predictors for individuals.

3.2.2 Summary of caries predictors

From the available evidence it would appear that:-

i) there are no reliable predictors for caries activity.

ii) initial caries prevalence in deciduous or permanent teeth has a high PV- and can be used alone or in conjunction with other markers such as age or obesity to identify low risk patients.

iii) microbial tests alone or in conjunction with other markers do not appear to be better predictors than initial caries prevalence and require more time and money to use them.

iv) lactobacillus tests together with intensive diet counselling may offer a practical method for reducing sugar intake in the default high risk group (Vanderas 1986; Abrams et al 1989). However although 4 dip slide tests cost only about £8-00 (Dentocult test, Rexodent) the costs of serial lactobacillus count monitoring of a high risk group involving conselling may be high and the administration in school-based programmes demanding.

3.3.1 Periodontal disease predictors

3.3.2 Plaque, calculus and gingivitis

The conventional clinical risk markers associated with periodontal destruction are plaque, calculus and gingivitis but unfortunately they are not reliable predictors of periodontal breakdown (Haffajee et al 1983a; Baderstein et al 1985; Lang et al 1986; Griffiths et al 1988).

Haffajee et al (1983a) monitored the periodontal status of 3414 sites in 22 adults at 2-monthly intervals. Neither gingival redness, plaque, suppuration or bleeding on probing possessed both high sensitivity and specificity (>= 0.9) and the authors concluded these indicators were unsuitable as predictors for destructive periodontal disease.

Baderstein et al (1985) investigated 49 patients with advanced chronic periodontitis. They monitored attachment levels every third month for 24 months and compared this to scores of plaque, bleeding, suppuration on probing and probing depth. Although there was a weak association between these scores and LPA, the predictive values were low with a PV+ for plaque, bleeding and probing depth being 12%, 25% and 35% respectively.

Lang et al (1986) reported that sites which bled on probing at 4 subsequent visits had a 30% chance of LPA, whereas sites which bled at one visit or not at all had less than a 3% chance of LPA.

3.3.3 Loss of periodontal attachment

Goodson et al (1982) investigated how the periodontal attachment level (PAL) varied with time by investigating PAL at 2 sites per tooth on 22 untreated subjects every month for 1 year. 83% of the sites did not change, 6% became significantly deeper and 11% became shallower. Half of the sites which increased exhibited a cyclic deepening followed by a spontaneous recovery to their original depth. The investigators concluded that periodontal disease was a dynamic condition with periods of exacerbation, remission and inactivity.

Socransky et al (1984) reported on LPA for 64 patients examined over 6 years. They found that 12% of sites suffered more than 2mm LPA over this period. Of those that lost attachment in the first 3 years only 40% lost further attachment in years 4-6. In 50% of sites with no LPA in the first 3 years, LPA occurred in years 4-6. The authors concluded that random "bursts" of disease activity had occurred.

Goodson et al (1984) investigated the relationship between attachment level loss and alveolar bone loss on 22 untreated subjects. Sites were probed monthly and radiographs made at baseline, 6 and 12 months. A comparison was made between 10 sites which had radiographic bone loss of >= 0.48mm (3 SD) and measured LPA. It was found that a 4mm LPA had a PV+ of 60% and PV- of 95% for predicting bone loss in the following 6-8 months. However some caution should be exercised in accepting their conclusions since their sample size of 10 active sites is small. Also they used the tolerance method of dividing sites of LPA into

"active" and "inactive" which has been criticised as unreliable (Sterne 1988; Birkedal-Hansen et al 1988).

Although the conclusions regarding variations in destructive activity are now generally accepted (Johnson 1988), the assessment of LPA for an individual site should be treated with some caution since probing measurements have a large inherent error (Robinson and Vitek 1979; Listgarten 1980). Goodson et al (1982) reported for their work a mean PAL error of SD 0.84 mm.

3.3.4 Smoking

Ismail et al (1990) re-examined 167 adults 28 years after an initial examination to investigate which factors might be predictors for LPA >= 2mm per person. Although age, smoking, tooth mobility at baseline, gingivitis, plaque, calculus, educational level and dental attendance were considered, it was only the first 3 which were found to be significant predictors using regression analysis.

3.3.5 Radiographic loss of marginal bone

Albandar et al (1987) investigated the relationship between radiographic marginal bone loss and 7 possible predictors over a 2 year period in 180 adults. They found in order of best prediction initial bone level, age, sex, calculus, restoration margins and proximal surfaces explained 20% of the variance in longitudinal bone loss with the first 2 being the most important.

Recently Albandar (1990) compared radiographic bone height reduction of 142 subjects (18-67 years) over a 6 year period against the explanatory variables of presence of initial bone loss, local plaque retaining factors, age, sex, number of missing teeth at baseline and rheumatoid arthritis. Initial disease at baseline was defined as a cementoenamel junction (CEJ) to crest height distance >= 3mm and significant disease progression at a site being >= 1mm reduction in crest height over 6 years. The predictive value of the variables was assessed both at a subject level (proportion of sites changing) and at the individual site level. Using multiple regression analysis 61% of the variance for predicting the proportion of sites showing initial bone loss could be explained by age, plaque retention and the number of missing teeth, listed in order of importance. The same technique explained 53% of the variance for predicting the proportion of sites which would lose bone over time listing initial bone loss, plaque retention, age and rheumatoid arthritis as the important variables. Multiple logistic regression analysis showed that for predicting individual site loss, plaque retention and initial bone loss for that site had a much stronger effect than initial loss or local factors at other sites.

This may be an important discovery since it indicates a degree of independence between sites for disease progression using these markers. Unless systemic markers can be shown to influence disease progression greater than local factors then the hunt for simple prognostic tests could be futile. In this context simple means using general (not site specific) markers rather than site specific ones.

3.3.6 Systemic disease

Certain systemic conditions such as rheumatoid arthritis (RA) have been shown to be possible predictors of bone loss. Albandar (1990) found at the site level that RA and initial bone loss had equivalent values in explaining the variation of bone loss observed over 6 years. However, Albandar's initial findings were from a limited study of only 11 out of 142 people suffering from RA. A recent larger study of 37 RA patients and 37 age- sex-matched controls using multiple regression analyses showed that 26% of the variation in bone loss for the two groups combined together could be explained by age, diagnosis of RA, serum IgG antibodies to B.gingivalis and E.saburreum (Tolo and Jorkjend 1990). Of this variation age explained 14% and RA 6%. When the RA group was considered separately from the controls, the explained variation rose to 48%.

Diabetes mellitus may be another candidate for a high risk marker. In a study comprising 82 long- and 72 short-duration diabetics and 77 non-diabetic adults, increased bone loss was been found in the age group 40-49 years of long-term insulin dependent diabetics compared to age- and sex-matched controls (Hugoson et al 1989).

The prevalence of Type I insulin-dependent diabetes is 0.2% of the population aged less than 20 years-old and for rheumatoid arthritis 2.3% of adults peaking at 7% over 64 years-old (Weatherall et al 1988).

3.3.7 Microbiology

Although a number of organisms have been indicated in gingivitis (Slots 1979) and periodontitis (Slots and Genco 1984; Slots 1986 - section 2.4.2) considerable practical problems exist in trying to use microorganisms as predictors of disease. Moore (1987) in a review of the microbiology of periodontal diseases reported that over 300 distinct bacterial species have been found in the human gingival crevice. However, procedures vary greatly between different laboratories making comparisons of their results difficult. Socransky et al (1987) described how the complexity of the periodontal diseases were responsible for our lack of identification of any "certain" periodontal pathogens. In their paper they listed the major problems which they believed were responsible for the lack of progress. These were difficulty in taking samples from the crevice, dispersion of plaque samples, cultivation and identification of the organisms, complexity of the microbiota, mixed infections, opportunistic species, variation in disease activity, inability to differentiate between diseases in different subjects and the possibility of multiple diseases within the same subject.

The development of microbial markers is important for understanding the mechanisms of periodontal destruction. However, the problems outlined which need to be overcome before they can be used as a routine clinical tool are formidable.

3.3.8 Gingival crevicular fluid

In contrast to the microbial investigation of subgingival plaque, the collection of GCF on absorbent papers is a simpler task although care must still be exercised (Cimasoni et al 1988). Curtis et al (1989) in an extensive review of potential markers of disease from GCF concluded that further investigation was indicated regarding host enzymes which could affect extracellular matrix, the nature of glycosaminoglycans released into the GCF and the role of prostaglandin E2 in inflammation. However, no GCF predictive markers are currently available.

3.3.9 Summary of periodontal disease predictors

There are no accurate predictors of initial disease for a previously healthy site. Smoking, the diagnosis of insulin-dependent diabetes mellitus and RA may be useful for predicting destructive peridontal diseases at the subject level but further work is required to evaluate their predictive values. Although age has a strong predictive value it should be seen as a related factor but not directly a cause. A 4mm LPA has a moderate PV+ (Goodson et al 1984) but should be viewed against the limited 6-8 month period of warning which for the majority of patients who are examined at 6- or 12-monthly intervals would not be beneficial (Table 2.1). A person who is already being examined every 2 months for LPA would presumably already have been identified as a high-risk patient.

At the site level, local plaque retention factors and initial radiographic bone loss were good predictors for disease progression.

3.4 Summary of predictive tests

Caries predictive markers with a high PV- and moderate PV+ exist at the group level of subjects but the PV+ values are too low to reliably identify individuals at high risk. The tests are not predictive for specific sites but relate to the whole dentition. It is not clear whether the apparent failure of caries predictive tests is due to a low efficiency of the chosen markers for disease, unreliable clinical methods for detecting disease to validate the tests or a combination of both. Current clinical validating methods are unable to distinguish between active and inactive lesions which is an important deficiency. The exclusion of the earliest lesions from the diagnosis of disease occurs in the majority of the studies which may contribute to the poor performance of the prognostic indicators. The exisiting caries predictors may be useful for identifying the low risk groups and motivating a reduction in sugar intake for the "default" high risk groups.

There are no accurate predictors of initial periodontal disease for a previously healthy site. Systemic disease may be useful for selecting high risk people but further studies are required. At the site level, local plaque retention factors and initial radiographic bone loss were good predictors for disease progression.

3.5 Caries diagnostic tests

The following review concerns the commonly used caries diagnostic tests or new techniques which have been clinically tested.

3.5.1 Mirror and probe

The traditional method of diagnosing fissure, pit and approximal caries is by visual inspection with a mirror accompanied by tactile probing. The visual inspection may be preceded by an initial polishing and air drying of the teeth to remove debris and areas of staining. Regions of enamel colour change, surface pitting or frank cavitation are sought as evidence of carious destruction. However, early enamel caries is very difficult to detect visually in the walls of fissures or at approximal contact regions.

As a supporting test for suspicious areas, a sharp probe is often applied with considerable force to test for "sticky" fissures or frank cavitation of approximal regions. The theory behind this test being that carious tissue will provide a higher resistance to withdrawal of the probe than healthy tissue. However, Parfitt (1954) showed that 20% of teeth diagnosed as suffering from carious fissures were in fact sound while Miller and Hobson (1956) demonstrated 30% of the findings were false positives. Downer and O'Mullane (1975) compared visual examination alone against visual examination plus the use of a blunt probe. They found the specificity to be 0.81 and 0.85 for no probe and probe respectively, showing very little advantage from the tactile

test although the number of false positive approximal findings were reduced.

An in vitro experiment by Bergman and Linden (1969) demonstrated that 24 out of 30 white spot lesions could be converted into cavities by exploration with a probe under simulated clinical conditions.

The high number of false positives and the risk of converting early enamel lesions into cavities from sharp forceful probing indicate that this tactile method should be abandonned in testing for caries.

3.5.2 Fibre Optic Transillumination

Fibre optic transillumination (FOTI) is a comparatively new technique for diagnosing approximal caries. The basis for FOTI is that carious tissue has a lower index of light transmission compared to healthy tooth. When a bright light of about 0.5 mm diameter is placed just below the contact region, approximal caries can be seen as a dark area below the marginal ridge when viewed from the occlusal surface. FOTI has been investigated as a potential method for replacing radiography since it does not use ionising radiation.

Mitropoulous (1985) compared FOTI and bitewing radiographic examination for 50 patients aged 5 to 43 years. It was found that FOTI identified 85% of the radiographic dentinal lesions.

Stephen et al (1987) performed a similar comparison on 2247 children

aged 14 years and found that only 47% of the radiographic dentinal lesions were identified by FOTI. Perhaps more significantly only 17% of enamel radiographic lesions reaching up to the ADJ were detected by FOTI. These early lesions are of more significance since they have a higher probability of remineralizing than the dentine lesions. Stephen et al found that FOTI did increase the diagnosis of posterior lesions by 92% compared to a clinical examination alone but concluded that FOTI was not a substitute for radiography.

Sidi and Naylor (1988) performed a similar comparison of FOTI and bitewing radiography on 385 subjects aged 12-13 years of age. When the FOTI was performed from the buccal surface there was a 74% agreement between the two methods for dentine caries but this fell to 30% when illuminated from the lingual surface. If enamel lesions only were considered the agreement fell to 14% and 13% for the buccal and lingual approaches respectively. Sidi and Naylor concluded that the FOTI detected fewer lesions than conventional radiography and the FOTI was affected by alterations of technique. They supported Stephen et al (1987) in concluding that FOTI was not a substitute for radiography and poorly detected early lesions.

Sidi and Naylor (1988) did however make the point that radiography is not an absolute "gold standard" and had some reservations in using the comparative values as an absolute guide for evaluating FOTI. Indeed in a recent paper, endoscopically-viewed filtered flourescence (EFF) was compared against combined clinical, radiographic and FOTI methods for detecting approximal caries in 25 subjects aged 11 to 17 years

(Longbottom and Pitts 1990). EFF is a variant of FOTI which utilizes the fluorescence of enamel which occurs when it is exposed to blue light in the range 400 to 500 nm. Although the EFF method detected only 80% of the lesions (enamel and dentine) found by the combined methods it also detected an almost equal number of lesions which were undetected by the other methods. Further work is needed to determine the nature of these additional lesions.

In conclusion FOTI is a non-ionising radiation technique which is considerably less sensitive than conventional radiography in detecting early enamel lesions. It does not produce objective data to allow subsequent examination or comparison and its results are technique sensitive. Where radiography is not available it is useful in supplementing a clinical examination.

3.5.3 Electrical resistance

Pincus (1951) suggested that if an electric potential was applied to the occlusal fissures of a tooth, the resistance might vary between sound or carious tissue. Mayuzami et al (1964) showed that when a potential difference of less than one volt was applied, a resistance above 600 kilohms indicated a caries-free tooth while below 250 kilohms indicated dentinal caries. The alteration in electrical conductivity was suggested to be caused by saliva-filled spaces formed during demineralisation.

Rock and Kidd (1988) performed an in vivo study of 50 posterior teeth

(predominantly premolars) in children aged 13-15 years from a fluoridated area. The presence of cavitation or staining was recorded for each tooth followed by examination with FOTI, bitewing radiography and electrical resistance using a Vanguard machine (no longer commercially available). The teeth were extracted and examined histologically with 37 showing demineralisation but only five of these had dentinal involvement. Clinically 6 teeth had stained fissures, one tooth had an FOTI shadow and no radiographic lesions were found. In contrast the Vanguard resistance meter reported 28 teeth with caries. The sensitivity of the electrical method was 70% and specificity 85%. The significance of these results is that they relate to very early caries except for the 5 teeth with dentinal demineralization.

In a further in vivo study of 50 premolar teeth which were subsequently histologically examined, it was found that a resistance below 5 megohms was positively associated with demineralization in the inner half of enamel or into dentine (Rock and Kidd 1990).

From the limited number of in vivo studies performed, the electrical resistance method would appear to potentially offer the best method for detecting quantitatively early occlusal caries. However, further studies are required to confirm these findings in molars and to investigate the problems of using this method in general practice.

3.5.4 Radiography

In this section only the clinical aspects of bitewing radiography will be considered as a review of radiographic methods follows in chapter 4.

Bitewing radiographs can be used for detecting occlusal and approximal caries in posterior teeth (Wuehrmann and Manson-Hing 1973).

King and Shaw (1979) examined 5,000 first molars clinically and then radiographically for signs of occlusal caries. One-third of the teeth clinically diagnosed as carious had occlusal radiolucencies and only 4% were diagnosed radiologically without clinical confirmation.

Sawle and Andlaw (1988) reported 10% of occlusal caries were diagnosed only from radiographs in a 1974 survey and a much higher proportion of 32% from a 1982 survey. They suggested that the higher figure in the later survey of only radiological diagnoses was due to fluoride toothpaste affecting the demineralising process making clinical visual diagnoses more difficult.

A recent paper by Creanor et al (1990) found that in 2623 subjects aged 14-15 years, 13% of lower first permanent molars which were diagnosed clinically as healthy had occlusal radiolucencies over dentine and this figure increased to 48% if the surfaces were discoloured but not cavitated.

These last 3 papers are important as they seem to demonstrate that visual diagnosis of occlusal caries is becoming more difficult and the number of radiographic-only diagnoses is increasing.

Several workers have emphasized that bitewing radiographs can underestimate the histological size of approximal lesions or can even fail to form radiolucencies (Marthaler and Germann 1970; Gwinnett 1971; Rugg-Gunn 1972; Buchholz 1977; Silverstone 1982).

A number of in vitro studies have provided different results regarding the ability of the bitewing technique to reveal approximal lesions. Van Aken (1966) compared 12 sound surfaces and 13 enamel lesions which were histologically validated against their radiographic images. The sensitivity and specificity for this small sample was 83% and 85% respectively. Leijon (1969) demonstrated that 27 out of 50 surfaces with white spot lesions in posterior deciduous and permanent teeth produced radiolucencies using different X-ray beam projections. Marthaler and Germann (1970) reported that 32% of white spot lesions produced a radiolucency. However, approximately one third of the surfaces examined were from extracted molars of an unknown age group. It is possible that if these teeth were from older adult patients, the white spot lesions would have remineralised apparently reducing the sensitivity of bitewings for detecting early caries (Kidd 1983). Gwinnett (1971) examined histologically 24 posterior teeth and concluded that lesions needed to penetrate greater than half the enamel thickness to produce a radiolucency.

Fewer in vivo studies have been formed and for ethical reasons histological validation is not performed or only on teeth extracted for orthodontic reasons. Downer (1975) compared visual and radiographic findings against histological examinations. However, enamel radiolucencies not involving the ADJ were counted as caries free preventing the results of this work from being included in this review of early lesions. Rugg-Gunn (1972) compared 370 visible white spot lesions on contact region surfaces with their bitewing images and found that 26% formed radiolucencies. In contrast Thylstrup et al (1986) found that 97% of 374 approximal surfaces with white spot lesions produced an accompanying radiolucency. The depth of the lesion and its surface integrity were judged by eye at the time of clinical tooth preparation. The large difference between these two studies may in part have been caused by two factors. The lesions in the non-contacting surfaces of Rugg-Gunn's study may have readily undergone remineralization reducing the radiographic contrast and sensitivity, since daily fluoride rinsing was performed. Conversely some of the lesions in Thylstrup et al's study may have undergone surface cavitation which was not seen by the observers which would have increased the reported sensitivity of the bitewing method.

In a recent in vivo study, Rimmer and Pitts (1990) compared the findings of a visual against a bitewing examination of primary and permanent teeth in normal approximal contact. They found that the radiographs revealed 88% more approximal dentine lesions (D3 diagnostic level) than would have been revealed by visual examination alone.

Kidd (1984) reviewed the diagnosis of the early carious lesion and reported on three of the above studies regarding depth of radiolucency and the percentage of surfaces which had cavitated (Table 3.2). Of these three studies, Bille and Thylstrup (1982) was the only clinical one with the teeth in correct contact and they reported that 80% of teeth with radiolucencies confined to enamel had not cavitated. As Rock (1987) commented, the traditional assumption that a radiolucency appearing over dentine indicated enamel surface cavitation which required a restoration was no longer supported by a critical examination of the available literature.

A recent paper (Kidd and Pitts 1990) reappraised the value of the bitewing radiograph in the diagnosis of posterior approximal caries. The authors reviewed 29 papers between 1933 and 1987 comparing the value of the bitewing radiograph and a clinical examination in the diagnosis of approximal caries. In 8 studies of children (spanning 3 to 8 years-of-age) radiographs revealed a high percentage of additional lesions over and above those seen clinically (range 40% to 469%) irrespective of age or diagnostic threshold.

When Kidd and Pitts (1990) evaluated studies involving permanent teeth, 18 out of 26 sets of results showed that more than a further 50% of lesions (over and above those clinically detected) were found using bitewings. Six of these studies showed an increased diagnostic yield of 250% more lesions from radiographs compared to clinical examination. Kidd and Pitts concluded that the clinical examination alone was unlikely to reveal more than half the total number of

lesions while bitewings could reveal in excess of 90% of the total number of lesions.

In conclusion, bitewing radiography as a diagnostic test for occlusal and approximal caries has a high specificity. Early occlusal lesions are unlikely to be detected because the images are complicated due to the 3D fissure pattern being reduced to 2D. Larger occlusal precavitated lesions involving dentine will produce radiolucencies in about one third of cases. Bitewing radiographs have a sensitivity of 75% ± 16% (Pitts 1984a) and a specificity of 85% or higher for approximal lesions.

Table 3.2 Correlation between radiographic appearance of approximal lesions and clinical condition of enamel surface (after Kidd 1984)

	Percentage of teeth with enamel cavitation		
	Marthaler	Rugg-Gunn	Bille
Radiolucency	1970	1972	1982
Confined to enamel	34	20	13
To amelo-dentinal junction	66	47	20
To outer half dentine	87	100	50

3.5.5 Summary of caries diagnostic tests

From this comparison of methods it would appear that bitewing radiography is the method of choice for detecting early precavitated approximal lesions since it has the highest sensitivity and specificity. Diagnosis of precavitated occlusal caries is poor by visual and tactile methods with false positives likely to result in unnecessary restorations. In addition probing has the risk of converting white spot lesions into cavities. Bitewing radiography has a high specificity and a low sensitivity to early occlusal caries, although there is mounting evidence to suggest they can detect up to a third of the lesions missed by visual inspection.

Electrical resistance methods may offer a significant improvement in the early detection of occlusal caries over other methods but further investigation is required.

It is concluded from this review of caries diagnostic methods that bitewing radiography is currently the best method available for diagnosing precavitated approximal lesions. In combination with visual examination, bitewing radiography will increase the sensitivity for detecting precavitated occlusal caries but the overall diagnostic accuracy is still less than ideal for this site.

3.6 Diagnostic tests for peridontal diseases

Similar to the review of caries diagnostic tests (section 3.5) only the most commonly used tests for diagnosing the periodontal diseases will be reviewed. New research methods using ultrasound (Palou et al 1987; Lost et al 1988) and thermal imaging (Barnett et al 1989) will not be reported on.

3.6.1 Gingival colour and texture

Wennstrom (1988) reviewed the role of gingival colour and texture in diagnosing periodontal disease. Traditionally pink stippled gingivae are indicators of gingival health but these may vary with the dimensions of the tissues, the extent of epithelial keratinization and the vascularity of the connective tissues. Smokers often have a thick keratin layer which can hide well developed inflammatory changes while healthy gingivae with a narrow zone of attachment can appear red. Age is often associated with a reduction of epithelial thickness and keratinization frequently accompanied by pigmentation which can cause gingival colour changes.

The clinical visibility of oedematous change within the connective tissues will depend on the morphology and keratinization of the gingivae and often obvious inflammatory swelling does not occur.

Gingival colour and texture changes cannot be considered as reliable diagnostic signs.

3.6.2 Bleeding on probing

Bleeding following subgingival probing is a common finding and the proportion of available sites which bleed in the mouth varies with time. Muhlemann and Son (1971) produced an experimental gingivitis in volunteers and showed that increased sulcus bleeding occurred over a 17 day period. This was measured by a sulcus bleeding index (SBI) designed by the authors based upon the presence of bleeding, gingival oedema and colour changes. Muhlemann and Son suggested that their index would provide a reliable early diagnosis of gingivitis.

The role of bleeding upon probing in the diagnosis of periodontal diseases has been reviewed by Greenstein (1984) and Griffiths et al (1988). These reviewers found that the width of a probe, the angulation and force of insertion could all affect the degree of bleeding produced. Standardized pressure probes have been used to overcome the variations in probing pressure. However, gentle probing can penetrate laterally through healthy crevicular epithelium producing bleeding from healthy underlying connective tissue. There are also conflicting reports in the literature concerning the relationship of bleeding and probing depths.

Lang et al (1986) were able to demonstrate a weak relationship between repeated bleeding at examinations and LPA. Sites which bled at every examination had only a 30% chance of LPA and sites which never bled had a 1.5% chance of LPA (see discussion on predictive values 3.3.2).

In summary bleeding upon probing is an unreliable method of accurately measuring the extent, severity and activity of periodontal diseases.

3.6.3 Periodontal probes

Periodontal probes are blunt measuring devices used for estimating gingival sulcus or pocket depths. The distance is measured from the free gingival margin (FGM) to the probe tip which is assumed to be touching junctional epithelium at the base of the pocket.

The LPA can be estimated by a two stage measuring process. First the CEJ is identified with the probe tip and the CEJ to FGM distance recorded. Secondly the probe is advanced to the base of the pocket and the distance to the FGM noted. The first reading is subtracted from the second to provide the LPA. If root surface is visible, a periodontal probe can also record the gingival recession from the CEJ to the FGM.

Periodontal probes record "probing depth" not pocket depth as it is recognised that visual and tactile identification of the CEJ, variation in probe position and inflammatory tissue changes are sources of measurement error (Listgarten 1980; Watts 1987). The consistency of the soft tissues varies with inflammation and the probe tip can pass through the superficial tissues until it reaches the most coronal intact dento-gingival fibres, approximately 0.3 mm to 0.5 mm apical to the apical termination of the junctional epithelium (Robinson and Vitek 1979; Listgarten 1980). Another source of error is

variation of probing pressure since an increase from 0.15 Newtons (N) to 0.75 N can increase probing depth of the same site by 2 mm or more (van der Velden and de Vries 1978).

The effects of these errors have been observed by performing duplicate probing measurements which revealed a non-Gaussian distribution preventing the use of simple SD thresholding to separate true change from measurement error (Janssen et al 1987). However, shallow probing depths of < 2.5 mm (Cohen and Ralls 1988) and < 3.0 mm (Janssen et al 1987) had a more Gaussian reproducibility variation.

Attempts have been made to reduce the errors due to variation in probe positioning by using occlusal stents and constant force probing but little difference in the overall reproducibility was found (Watts 1987). In addition Watts (1987) found that 2% of all probing depth measurements varied by 3 mm or more at the same site and similar to Janssen et al (1987) reported that deeper pocket measurements were more unreliable than shallow ones.

Recently a computerised constant force probe has been developed - the Florida probe (Gibbs et al 1988). Duplicate clinical measurements on 12 patients with early to minimal periodontal disease had a SD of 0.58 mm. When used with an occlusal stent the error was reduced to SD 0.28 mm. It would be interesting to see if this reliability was produced with subjects exhibiting moderate to severe disease.

The review of probing has so far shown considerable shortcomings with

regard to accurate monitoring of disease progression or activity. However, a clinical role exists for probing using the Community Periodontal Index of Treatment Needs (CPITN).

The CPITN probe has been developed with coarse measurement intervals of 3.5 mm and 5.5 mm from a 0.5 mm diameter ball-ended tip for assessing community treatment needs (Cutress et al 1987). It can be used as a screening procedure for populations or in dental practice for assessing treatment needs. Either part-mouth scoring on specific index teeth or whole mouth examinations can be performed recording the worst score for each sextant. The scores are periodontal health (0), bleeding following gentle probing (1), calculus or presence of plaque retentive factors (2), mild pocketing < 6 mm (3) and pocketing >= 6 mm (4). From these scores the sextants are allocated a treatment need category which are no treatment needed (0), oral hygiene instruction only (1), scaling and removal of other plaque retentive factors (2 and 3) and complex therapy (4). Griffiths et al (1988) reviewed the criticisms of the CPITN method and noted that the use of a part-mouth scoring system leads to overestimation of treatment needs, the index uses probing depth and not attachment levels which are better indications of LPA, mild pocketing is defined as up to 5.5 mm which some clinicians would regard as excessive and there is no distinction between supra- and subgingival calculus.

In summary the CPITN method provides a simple and quick method for estimating treatment needs but it is not capable of monitoring small amounts of LPA. Probing methods in general are unreliable with errors

of 0.6 mm and above being a poor guide to establishing true variation. There is evidence to suggest that in pockets over 3.0 mm the error distribution is non-Gaussian. No methods have been devised to reduce the variation of tissue consistency due to inflammatory changes.

3.6.4 Radiography

In this section only the clinical aspects of conventional radiographic techniques will be reviewed. Factors affecting the validity and reliability of radiographic images together with new techniques will be considered in chapter 4.

Unlike caries diagnosis, which almost exclusively uses bitewing intra-oral films, alveolar bone crests can be assessed from intra-oral periapical and bitewing films as well as from extra-oral panoramic views.

The use of dental panoramic tomography (DPT) for assessing alveolar bone crests has been reviewed by Hirschmann (1987b). He noted that despite a one third lower radiation dose from DPT compared to a complete mouth periapical survey, the use of intensifying screens leads to loss of fine detail in the image. It is more difficult to standardise DPT images compared to intra-oral methods and early marginal bone loss is often underestimated. Hirschmann (1987b) and Akesson et al (1989a) recommended that DPT be combined with intra-oral films for selected regions, where the images were lacking in detail, to maximise diagnostic yield with the minimum radiation

exposure.

Periapical or bitewing intra-oral films are the conventional method for investigating alveolar bone changes due to periodontal disease. The choice of film and exposure technique are important as they affect distortion of the image. The bisecting angle method produces a central ray which is oblique to the alveolar crest margin (ACM) and underestimates the crest position (Lang and Hill 1977). Hausmann et al (1989a) investigated the relationship between irradiation geometry and ACM using dry skulls (section 4.3.2.4). It was shown that the bitewing rather than the periapical film position was most likely to produce the least distortion due to the X-ray beam being more tangential to the ACM and the film. For teeth suffering from extensive loss of bony support, a horizontal bitewing film can still be used. The film, in a modified bitewing holder, is displaced 5 mm in the vertical plane towards the quadrant of interest. This ensures that almost the entire length of the tooth roots in one posterior quadrant are visible while still maintaining a favourable irradiation geometry (- unreported work in progress).

Early periodontitis may cause crestal bone loss, marginal widening of the periodontal ligament space (PLS) and crestal irregularity.

3.6.4.1 Crestal bone loss

Traditionally dentists have measured the radiographic distance from the CEJ to the ACM and used a pre-set threshold for indicating

evidence of past disease. This pre-set distance has no concensus with workers using different values; Lennon and Davies (1974), Hugoson and Rylander (1982), Mann et al (1985) 1.0 mm; Davies et al (1978) 1.5 mm; Hoover et al (1981), Kronauer et al (1986) 2.0 mm; Blankenstein et al (1978), Latchman et al (1983) 3.0 mm.

Radiographic surveys have been performed using a variety of protocols for estimating CEJ to ACM distances with a range of measurement errors from SD 0.02 mm to 0.47 mm (Table 3.3). A variety of different reference sites have also been chosen to measure crestal bone height changes.

Selikowitz et al (1981) measured from the highest point of an occlusal tooth surface to the highest point of the ACM and also to the most occlusal point of the PLS where it was of a constant width. A total of 100 pairs of serial unstandardised bitewing radiographs were measured covering a 10-year interval and the annual rates of loss found to be approximately 0.05 mm. However, details of the measurement reliability were not reported.

Al-Kufaishi et al (1984) measured from the occlusal surface of a Backer-Dirks film holder to the top of the interdental crest and also to the top of the PLS where a constant width commenced. The use of a high contrast straight edge from the Backer-Dirks holder considerably reduced the variation in identifying one of the reference points which in part explains the very high reliability of SD 0.02 mm (Table 3.3). Al-Kufaishi et al (1984) reported statistically significant

incremental changes in crest height of the order of 0.25 mm from serial pairs of bitewing radiographs in 174 11-14 year-old children.

Clerehugh and Lennon (1986) compared the radiographic measurement of early periodontal bone loss and its relationship with clinical LPA in 68 13- to 14-year-old subjects using serial pairs of unstandardised bitewings. They used enlarged tracings of the approximal surfaces of the first molar and adjacent premolar together with crest margin outline to examine height changes. The CEJs were joined by a line across the interdental space and then a perpendicular line of known length dropped to the highest point of the crest margin. This procedure was repeated for the later film of the pair and the measurements compared to detect crest height change. Clerehugh and Lennon (1986) reported that a 1 mm LPA was associated with a crest height reduction of 0.5 mm. However, the reliability of their radiographic measurement technique was not clearly quantified.

Clark et al (1990) compared the areas of magnified sequential tracings to estimate changes in ACM. The reliability of the method was SD 0.12 mm^2 which was within the range 0.03 to 0.20 mm^2 reported in 3 other papers (Clark et al 1990).

Table 3.3 Range of measurement reliabilities reported from eight radiographic studies of alveolar crest margin height.

Author	(SD)mm	Measurement method	Film	Stnd irrdn geometry
Al-Kufaishi et al 1984	0.02	M x12	BW	Backer-Dirks
Fredrikson et al 1989	0.15	DP x5	BW	None
Goodson et al 1984	0.16	DP x7	PA	Occl stents
Hausmann et al 1989	0.35	DV -	BW/PA	?
Albandar et al 1986a	0.37	M x10	PA	Eggen holder
Papapanou et al 1988	0.44	M x10	BW/PA	Eggen holder
Teiwik et al 1984	0.45	M x10	BW	None
Wouters et al 1988	0.47	DP x5	PA	None

Key: (SD)= standard deviation; M= manual measurement using ruler; DP= image projected onto digital plotter; DV= digitised video image mouse measurements; xn= magnification.

3.6.4.2 Marginal widening of the PLS

Van der Linden and van Aken (1970) performed in vitro experiments and concluded that the apparent marginal widening arose from an error of visual assessment due to the high optical density of the image at that region. Al-Kufaishi (1982) measured 89 bitewing radiographs of 11-14-year-old children and found the PLS to be 0.25 mm wide at the crest and 0.16 mm at its narrowest in a more apical position indicating that the greater marginal width was a consistent feature and not an optical illusion. Al-Kufaishi (1982) also attempted to

separate physiological from pathological widening of the PLS by selecting a threshold width of 0.53 mm (0.25 mm + 2SD[0.28 mm]). He found that only 4.5% of the sites had a PLS wider than 0.53 mm. Hirschmann (1987a) suggested that such accurate assessment of PLS width changes should only be attempted on serial films. Al-Kufaishi (1982) examined 174 11-14-year-old children using serial bitewings from a 3-year survey. He reported a statistically significant widening of the PLS at the crest margin of the mesial surface of the maxillary first molars but not on the distal surfaces concluding that this was not a reliable measure for early periodontitis. This may not be a valid conclusion, since one could possibly explain the unreliability of the distal surface being related to an unfavourable irradiation geometry and not to a fault of the measuring method.

3.6.4.3 Crestal irregularity

Greenstein et al (1981) stated that the interdental alveolar crest is often described as possessing a thin continuous corticated radio-opaque border or lamina dura. Greenstein et al (1981) examined 2189 crests from 90 people with a mean age of 31 years using full mouth standardised periapical and bitewing radiographs. They found no significant correlation between presence of an intact lamina dura and presence or absence of clinical inflammation, bleeding on probing, pocketing or LPA. Ainamo and Tammisalo (1973) and Mann et al (1985) compared the presence or absence of an intact lamina dura to the diagnosis of periodontal disease. Both groups used single bitewing radiographs preventing a serial time assessment from being made.

Ainamo and Tammisalo (1973) used Gingival Index scores (Loe and Silness 1963) to diagnose clinical periodontal disease and Mann et al (1985) used a LPA over 1 mm as the clinical criterion. Both research groups reported no significant relationship between the intactness of a lamina dura and the state of the periodontal tissues. However, gingival changes and small changes in attachment levels are unreliable indicators of disease (sections 3.6.1, 3.6.2 and 3.6.3) and one must question their use for validating potential radiographic features for diagnosis of disease.

Stoner (1974) recorded the presence of an intact lamina dura in only 38% of 383 crestal sites in 40 children aged 4 to 15 years-old using unstandardised bitewings. Stoner also investigated the crestal site between the lower right primary molars of 4 dry skulls using a standardized technique with a variable vertical angulation of $+45^{o}$ to -15^{o}. In 3 out of 4 skulls, a lamina dura was visible but as the vertical angulation varied from the horizontal the radiographic feature disappeared.

Al-Kufaishi (1982) examined 136 serial pairs of bitewing radiographs for an association between loss or gain of crest bone height and change of lamina dura. No relationship was found. Al-Kufaishi also investigated 350 mesial and distal intercrestal regions of teeth 16 and 26 (FDI notation) in serial bitewing films for evidence of development of crestal erosions. It was found that 14% of sites had erosions at the angle of the crest with the PLS and almost half of these enlarged over the 3-year study period. Al-Kufaishi proposed that

initial marginal loss is likely to appear as loss of lamina dura in this region.

In summary 7 studies have shown that intra-oral radiographs magnified 5 or more times can be used to measure the CEJ to ACM distance to a reliability of between 0.02 mm and 0.47 mm. However, no digital image method has achieved a reliability of SD 0.15 mm for every available site. Marginal widening of the PLS in a small percentage of sites has been observed in one study using serial films but the reliability was site dependent. Crestal irregularity has been reported from several studies but the significance is unclear due to different protocols and the use of unreliable clinical criteria to validate the radiographic observations.

3.7 Summary of periodontal diagnostic tests

The conventional diagnostic tests of gingival colour, texture and bleeding on probing are unreliable indicators to the presence of active periodontal disease. Periodontal probing measurements are also unreliable and unable to measure accurately the extent of tissue destruction from past or present disease activity. Only radiography is capable of revealing the structure of interdental alveolar bone in a stable image capable of providing objective analysis and reliable CEJ to ACM measurements for assessing crestal changes. Contrary to traditional teaching there is some evidence to suggest that early loss of ACM may be detectable radiographically.

3.8 Summary of predictive and diagnostic methods

The current failure to develop accurate predictive tests for initial caries and periodontal destruction (section 3.4) inevitably leads to an immediate requirement for dentists to use accurate diagnostic tests for dental disease. A review of existing clinical methods has shown that all are inadequate. Bitewing radiographs provide the best method for detecting approximal caries although they have a low sensitivity for occlusal caries. However, fluoride may now be making visual identification of fissure caries more difficult increasing the number of radiographic-only diagnoses of occlusal caries.

Bitewing radiographs seem to offer the best opportunity for detecting early interdental ACM changes. Although radiography from neccessity uses ionising radiation, the use of faster film speeds, rare earth beam filters, tight collimation and correct exposure technique can considerably reduce the risk of radiation-induced death to less than 0.33×10^{-6} which is the current risk from 2 bitewings (Wall and Kendall 1983).

This chapter has reviewed the important role that intra-oral radiography has in diagnosing dental disease. In the next chapter those factors which affect the validity and reliability of radiographic images and measurements will be reviewed together with new techniques.

Chapter 4 Review of the literature relating to radiographic methods for diagnosing caries and periodontal diseases.

4.1 Introduction

Radiology is the interpretation of 2D or 3D images, created by the differential attenuation of X-ray and gamma ray photons in anatomical structures. Since X-rays are well attenuated by dense tissues, radiology has been successfully used to investigate the structure of tooth and bone since the beginning of this century (Kells 1899; Raper 1925).

Dental X-rays are produced by bombarding a tungsten anode target by high energy electrons accelerated by an electric field of 50 kV to 90 kV (Williams 1969). After appropriate filtration, to remove harmful low energy photons, the X-rays produced are collimated to a small beam, further reducing unnecessary radiation to the patient, and directed to the area of interest. Silver bromide films are used conventionally to capture an image either extra- or intra-orally.

Extra-oral 2D images can either be produced by stationary or mobile X-ray apparatus. Stationary generators and sensors are used for producing images which are projections of the skull and jaws. A linked moving X-ray generator and sensor with slit beam can be used to produce a curved vertical slice through the jaws, to produce a dental panoramic tomograph (DPT). This has the advantage of producing a survey from a 3D path coinciding with areas of interest of the teeth,

jaws and facial structures, resulting in a single flat image for convenient viewing. More complicated techniques are available to reconstruct 3D models of the head and neck, such as computerised axial tomography (CAT scans) or magnetic resonance imaging (MRI) but these will not be included in this review.

Intra-oral images can be produced from a stationary extra-oral generator and a film or sensor placed inside the mouth. The 2 most common intra-oral techniques produce radiographs from the bitewing and periapical film projections. Bitewing films are so-called because a paper tab or wing protudes from the film packet surface, to enable the teeth in occlusion to retain the film in the desired position. Most commonly the bitewing technique is used in the posterior region of the mouth where ,ideally, the central long axis of the film coincides with the occlusal plane on biting. In this manner equal amounts of coronal tooth and alveolar crest margin tissue are projected onto the film for the premolars and molars. Bitewing radiographic images can also be made with the long axis of the film vertical to the occlusal plane to include more apical extents of alveolar bone but covering fewer teeth than the horizontal position. For views of tooth apices the film can be placed either horizontally or vertically such that the periapical region is projected onto the film. If the film is parallel to the long axis of the teeth and the X-ray beam | normal to the film, this is termed a paralleling periapical projection. However, if the beam is tangential to a line midway between the long axes of the teeth and film, it is called a bisecting angle projection. A modified bitewing position can be used for examining posterior regions with

moderate to severe alveolar bone loss which favours reproducible irradiation geometry with the least alveolar crest margin distortion (section 3.6.4 and Appendix V).

4.2 Dental panoramic tomography

The principal advantages of DPT compared to intra-oral radiography are that in a 15 second exposure, a large area survey of the facial region can be obtained with approximately one third of the dose from an 11 film periapical survey (Hirschmann 1987b).

However, there are many disadvantages of the DPT method compared to using intra-oral film for detecting caries or early bone loss. The DPT images have unequal distortions in the horizontal and vertical planes which are inherent to the method of producing the tomograms (Welander et al 1982). Unsharpness is caused by the focal-spot size, focus-object-film geometry, intensifying screens, scattered radiation, patient movement and tomographic movement blurring (Hirschmann 1987b). As a result of these limitations, DPT images will always be less sharp than screenless intra-oral films.

Several authors have compared the estimation of alveolar bone loss from DPT and intra-oral films. Kaimenyi and Ashley (1988) examined DPT images from 50 patients aged 30-39 years. They reported that radiographic CEJ to alveolar crest margin measurements underestimated direct surgical measurements by a mean of 1.6 mm and that 26% of radiographic sites were excluded since the CEJ region was not visible.

Akesson et al (1989b) compared posterior bitewing radiographs against DPT images from 100 patients with a mean age of 37 years. They used a proportional measurement ruler to assess loss of marginal bone (Hakansson et al 1981). Similar to Kaimenyi and Ashley (1988) they found the CEJ difficult to identify on the DPT images. Approximately 70% of the crestal scores were the same for both radiographic techniques and when they differed, the DPT images showed a greater degree of bone loss which the authors considered were false positives.

Akesson et al (1989a) reviewed 9 papers regarding the percentage of uninterpretable sites for assessment of alveolar crest margin from DPT, periapical and bitewing methods. The DPT had a higher proportion of unreadable sites compared to the intra-oral methods with the upper arch worse than the lower (Table 4.1).

Douglass et al (1986) compared the diagnoses of caries and periodontal bone loss from DPT, periapical and bitewing radiographs from an examination of 602 men aged 28 to 76 years. No validating method was used, such as histological examination, and the "correctness" of the diagnosis depended on concensus where after reading each different film type separately, they were read together. This approach does not reveal the true diagnostic accuracy of the different film methods but it does allow a comparison between them. The caries disease threshold was set at D2 (radiolucency over outer dentine) and periodontal threshold of complete loss of crestal cortical bone or a CEJ to alveolar crest margin distance > 2 mm. The most sensitive method for diagnosing caries (all surfaces) was the bitewing technique (59%)

followed closely by periapical (53%) but DPT performed poorly (22%). All three methods had a high specificity of over 97%. Periodontal sensitivity was high for all 3 methods at approximately 85%. However, the specificity was in decreasing order highest for periapical films (80%), followed by bitewings (69%) and lowest for DPT images (46%). These data suggest that intra-oral radiographs have a higher diagnostic accuracy than DPT images.

Table 4.1 Summary of unreadable sites for assessing alveolar bone margin loss from three different radiographic methods.*

Panoramic		Periapical		Posterior bitewing	
Upper arch	Lower	Upper arch	Lower	Upper arch	Lower
%	%	%	%	%	%
28	15	12	8	17	26

* Mean values derived from review of 9 surveys from Akesson et al 1989b.

In summary DPT images have a lower spatial resolution than intra-oral films and are difficult to standardise the irradiation geometry. Frequently there is loss of the CEJ reference site required for accurate crest height assessment and overestimation of bone loss. From these observations it would seem that intra-oral screenless films are preferred to DPT images for accurate measurements. Caries has

traditionally been diagnosed from bitewing images due to the requirement of a high resolution image for defining the edges of a lesion. DPT does have a useful role screening for large scale structures such as buried teeth, roots, cysts and neoplasms. However, accurate diagnosis and monitoring of caries and periodontal disease requires sub-millimetre accuracy (sections 2.3.5 and 2.4.8) which is unlikely to be attained from panoramic techniques and the rest of this review will now concentrate on intra-oral techniques.

4.3 Intra-oral radiography

Intra-oral radiography will now be reviewed according to the following categories:-

i) types of image sensors.
ii) factors affecting image formation.
iii) radiographic measurement methods.
iv) image processing techniques.

4.3.1 Image sensors

Any device which converts X-ray photons into an image form suitable for human viewing can be termed an image sensor/ display combination. Three image sensors in clinical use will be reviewed; X-ray film, Xeroradiography and solid state devices.

4.3.1.1 X-ray film

In April 1896 *Eastman* produced the first dental X-ray films in the United States on pieces of photographic glass and wrapped in black paper and rubber dam (Eastman 1970). In 1913 handmade prepackaged dental film appeared which was replaced in 1919 by an emulsion designed for exposure by X-rays and had a lead foil inside to reduce backscatter. The Eastman Ultra-speed "D" periapical film was released in 1941 and has changed very little over the years except for a faster "E" emulsion and soft packaging.

The gelatin-based film is coated on both sides with a silver halide emulsion which converts approximately 1% of the incident radiation into chemically processed black silver grains producing a visible radiograph. The flexible film packets can be deformed slightly for comfortable positioning in the mouth and if only light pressure is used no visible image faults will be produced. Once a film has been exposed the latent image is stable for months providing it is kept cool and away from any sources of radiation. Providing the darkroom processing and washing is performed according to the manufacturer's instructions, a radiograph may be stored safely for years without risk of image degradation.

The physical response of radiographic film to radiation can be described by its sensitometric properties. These can be defined in terms of density, speed, contrast and resolution (see Appendix I for definitions).

Kodak intra-oral "D" and "E" speed films have a resolving power of about 20 line pairs per mm (lp/mm) which can be produced by a test grid and seen using a magnifying viewer (Jensen 1980). At this high resolution the alternate light and dark bands are only 0.025 mm wide which is far smaller than the size of dental anatomical structures which are likely to be found in clinical radiographs. For most purposes a resolution of 10 lp/mm or alternate bands 0.05 mm wide should be adequate.

Intra-oral screenless silver halide films are capable of producing excellent high resolution images with a good contrast range (Frommer and Jain 1987). Its principal disadvantages are that i) correct chemical processing is demanding and requires from 5 minutes to 1 hour to produce a dry film depending on whether automatic or manual processing is used and ii) excessive radiation to a region can cause blackening or "burn out" of the image losing anatomical information.

4.3.1.2 Xeroradiography

Xeroradiography was introduced as a new dental radiographic technique about 15 years ago (Gratt et al 1978; Jeromin et al 1980). Instead of a silver halide film emulsion it uses a charged selenium photoconductive plate to form a latent image following exposure to X-rays. The exposed plate in a light-tight cassette is placed inside a machine, similar to a photocopier, which uses a toner to produce a visible image in about 90 seconds. The plate is then sterilized with ultraviolet radiation, cleaned of residual toner and exposed to light

to erase any residual charge.

Xeroradiographic images exhibit the unusual image characteristics of edge enhancement and deletion which are due to the electrostatic process (Pettigrew et al 1985). Edge enhancement is the deposition of extra toner at the margin of a density change on the charged plate. Deletion is the opposite situation where on the other side of the density change a region free of toner deposition occurs. The net effect is to produce an excessive contrast change across all image feature boundaries making even small differences in radiographic density obvious to the eye. This produces a wide exposure latitude so that boundaries between widely varying densities such as soft tissue and bone can be seen.

Pettigrew et al (1985) in a review stated that the resolution of high spatial frequencies in xeroradiographic images could be as high as 50 lp/mm and this was responsible for the better diagnostic images of bony trabeculae compared to film. Kashima et al (1985) compared the power spectrum and spatial frequencies of film and xeroradiographic images and concluded that the latter had a better high frequency response at 6 cycles/mm explaining the better trabecular bone images. Unlike film images which can easily produce dark regions or "burn out", xeroradiography saturates at about 1.9 optical density units making overexposure difficult (Gratt and Sickles 1983). In a recent paper, Shearer et al (1989) compared images of approximal caries exposed simultaneously with a combined "lead-less" film and xeroradiography cassette using an objective image analysis system. It

appeared that the xeroradiographic system was more sensitive showing a statistically significant greater area and degree of demineralization than film although there was no validating histology performed. Xeroradiography is a low dose method since it has a film speed approximately equivalent to "E" speed film (Gratt 1985).

There are a number of disadvantages with xeroradiography. Pettigrew et al (1985) reported that low spatial frequency features, such as the maxillary antrum, were better represented in conventional film. This is due to saturation of the selenium detector at low X-ray doses making it difficult to show large regions of different attenuation as different optical densities. There are also some problems using xeroradiographic processors since between 17% to 30% of images produced have artificial spots or lines and they break down more frequently than automatic film processors (Gratt 1979; Gratt 1985). Although an image can be produced quickly it cannot be stored as a latent image for longer than 5 minutes without risk of serious image degredation, unlike film (Gratt et al 1982). As well as improving resolution, the edge enhancement effect can also produce false caries-like radiolucencies at the margins of metal restorations which could result in unnecessary treatment. The selenium cassettes are bulkier than the equivalent number 1 and 2 sized film packets and have a reduced image area (Pettigrew et al 1985). In addition xeroradiography processors are more expensive than intra-oral automatic film developers.

In summary xeroradiography has a better subjective image than films

with an ability to reveal hard and soft tissues in the same image. Over exposure tolerance is good with little cervical "burn out" and the production of images is rapid. However, images must be processed immediately, frequently have marks on them, use bulky cassettes with small images and the xeroradiography system is expensive to buy.

4.3.1.3 Solid state devices

Solid state devices are silicon-based integrated circuits. Charge coupled devices (CCD) are a form of solid state device which can be sensitive to electromagnetic radiation. In dentistry CCDs which are sensitive to light and X-ray radiation are of particular interest. At the present time there are no readily available commercial intra-oral devices for directly converting X-ray photons to an electrical signal, although prototypes do exist. However, light sensitive CCDs are available as intra-oral devices which have an X-ray sensitive phosphor screen in close proximity to the chip surface (Radiovisiography, Trophy Ltd, Wembley). When X-ray photons hit the rare-earth intensifying screen (25 mm x 16 mm) it fluoresces and light is conducted down an array of optical fibres to the CCD surface. The X-ray exposure is synchronised to read out a video image signal from the intra-oral device which is displayed immediately on a computer monitor to a pixel resolution of approximately 256 x 256 at 256 grey levels (Mouyen et al 1989).

Initial independent evaluations of the Trophy system have been made by Horner et al (1989) and Shearer et al (1990). The resolution of the

system in normal mode was found to be 5 to 6 lp/mm or 7 to 8.5 lp/mm in "zoom" mode (Horner et al 1989).

The principal advantages of the Trophy method are its almost instantaneous production of a viewable image and 15 seconds to produce a permanent photographic quality image of the screen. Software manipulation of the image could be performed but currently there are no useful functions available. Horner et al (1989) concluded that the system subjectively produced clinically acceptable periapical images in a clinical trial of 60 patients. Shearer et al (1990) in vitro compared conventional film and Trophy images reporting that root canals could be seen equally well with both methods.

A disadvantage of the Trophy system is that at the moment the sensor is small, approximately one third the area of a number 2 size periapical film and is the principal cause for retaking images (Horner et al 1989). Normal bitewing views are not possible and the system is primarily restricted to single tooth periapical views. The sensor is bulky being 1 cm thick and has to be wrapped in a rubber sleeve as it is not sterilizable.

In summary the removal of chemical processing is a major advance since few dental practices produce optimally developed images (Dental Practice Board 1990). The rapid production of images is extremely useful for immediate diagnosis. Ideally, larger sensors are required for bitewing views and higher resolution images. Doubtless as manufacturing costs decrease these limitations will disappear and

eventually silver halide film will become obsolete with CCD or similar devices replacing them.

4.3.1.4 Summary of image sensors

Silver halide film is likely to remain the standard dental X-ray sensing method for at least the next 5 years until CCDs or other film alternatives become cheap enough to replace them. The principal disadvantage of film is the care required during chemical processing. Existing CCD technology is already clinically useful and once the resolution increases towards 10 lp/mm it will approach the performance of film. Although xeroradiography is superior to film in exposure latitude, it is unlikely to challenge CCD sensors.

4.3.2 Factors affecting image formation

Images formed from intra-oral radiographs can be affected by properties of the X-ray equipment, the exposure technique and processing methods (Manson-Hing 1985).

4.3.2.1 X-ray generator

X-rays are not generated from an infinitely small point source but a small area on a tungsten anode target, which produces an effective focus of about 0.6 mm x 0.6 mm. This produces a shadow with an unsharp edge or penumbra around objects seen in radiographs. The size of the penumbra is proportional to the size of the focal spot and inversely

proportional to the focus to object distance. A modern X-ray generator with a focal spot of 0.6 mm used with a focus to object distance of 300 mm and an object to film distance of 10 mm will have a penumbra width of 0.02 mm. For comparison, the light and dark bands of a 10 lp/mm test grid are each 0.05 mm. A short cone technique of 150 mm (0.04 mm penumbra) will limit the resolution to 10 lp/mm or below and shows the importance of using a small focal spot together with medium or long cone technique to permit adequate resolution.

4.3.2.2 Film density and contrast

Film density (see Appendix I) increases with higher kilovoltage (kV), milliamp current (mA), exposure time (seconds S), film speed and developing time. It decreases with overfixing, dense objects and long tube to film distances (Manson-Hing 1985).

Image contrast is most affected by the kV where increasing contrast range (number of grey levels) is caused by increasing kV and vice versa. However, the higher the kV the lower the resolution and a compromise of 65-70 kV is normally recommended (Thunthy and Manson-Hing 1978).

4.3.2.3 Chemical processing

X-ray developer is extremely sensitive to temperature and the contrast/density of a film will increase with time, temperature and solution concentration. Exhausted developers produce less dense poor

contrast images often with increased fog levels (Manson-Hing 1985). Cleanliness is essential since chemical contaminants readily reduce image quality. Adequate fixation, washing and adherence to manufacturers instructions regarding use of their chemicals will ensure good results with hand processing being preferred to automatic since this avoids roller marks.

4.3.2.4 Irradiation geometry and film position

Irradiation geometry describes the relationship between the X-ray beam, anatomical structures under examination and the radiographic film or sensing device.

Leijon (1969) radiographically examined in vitro 50 white spot lesions in approximal surfaces of primary and permanent posterior teeth. A single X-ray projection for each tooth failed to reveal any approximal radiolucencies but when each tooth was rotated about its long axis and 7 different projections made, 27 out of 50 of the teeth produced radiolucencies.

Sewerin (1981) radiographed in vitro 22 posterior permanent teeth containing 34 approximal white spot lesions or "minor" cavities. Each tooth was irradiated 16 times with the horizontal angulation of the X-ray beam varied in increments of 2.5 ^{o} over a total range of 37.5 ^{o}. In 71% of the lesions, an X-ray beam deviation of 7.5 ^{o} or less produced a different radiographic score.

McDonald (1984) investigated 11 child skulls aged 5-9 years for the relationship between deviations in X-ray angulation and images of approximal overlapping on bitewing radiographs. The skulls were irradiated and the X-ray beam varied horizontally in 2.5 ^{o} increments. It was concluded that an increase in overlap width of 0.1 mm was caused by an angulation change of less than 2.5 ^{o} in 95% of instances.

Stoner (1974) demonstrated that alterations in vertical angulation of the incident beam could produce loss of the lamina dura in dry skulls (section 3.6.4.3).

Sewerin (1983) compared the radiographic CEJ to alveolar crest margin distance on 1,236 bitewing and periapical radiographs from the same patients. It was concluded that 25% of periapical views underestimated bone loss by 1.5 mm compared to bitewings and that the distortion was worst for maxillary molars.

Sewerin (1987) performed in vitro experiments to investigate the influence of X-ray beam projection angles upon the position of the radiographic CEJ. It was found that changing the vertical angulation from 0 ^{o} to 20 ^{o} on 20 posterior permanent teeth produced an average reduction of 2.2 mm to 4.1 mm in CEJ to alveolar crest margin distance.

Hausman et al (1989a) made intra-oral radiographs of posterior teeth in 6 dry skulls with a known vertical angulation. A method was developed based on radiographic cusp height ratios to determine the

X-ray beam angle relative to the alveolar crest margin. The method was applied to full mouth surveys from 39 adults to determine the incident beam angles. It was concluded that bitewing X-ray beam angulation was between 90 ^{o} and 80 ^{o} and periapicals between 90 ^{o} and 70 ^{o} . A recommendation was made that to reduce the CEJ to alveolar crest margin distortions, the paralleling bitewing technique should be used.

In summary, changes in irradiation geometry can either increase or decrease the sensitivity of a radiographic sensor for detecting early disease changes. The paralleling long cone bitewing technique should be used to reduce CEJ to alveolar crest margin distortions and a repositionable film is essential for preventing artificial disease changes. Although an association between caries radiographic scores and X-ray beam variation has been reported, no detailed investigation of this has been made with histological validation. A detailed in vitro investigation is reported in Appendix IV.

4.3.3 Repositionable X-ray film holders

From the preceding section, it is clear that variation of the irradiation geometry between serial films could be a source of diagnostic error and a standardized positioning method is required. Pitts et al (1989) has shown how the use of paper bitewing tabs produce more image variation than using beam aiming devices.

Ideally a repositionable film holder should be quick and easy to use, indicate the position for the collimator tube and relocate accurately

relative to the teeth. In addition an aluminium or copper step wedge may be required as a reference for comparing image densities between films.

Many intra-oral film holders have been designed for both bitewing (review: Pitts 1984b) and periapical views (Price 1975; Duinkerke et al 1977; Duckworth et al 1983). The majority of the holders have incorporated a platform for retaining an impression material which on setting in the mouth has formed an intra-oral relocatable stent. Extra-oral relocating methods have been devised using a cephalostat (Jeffcoat et al 1987) and ear plugs (Pitts et al 1989).

Relocation using impression materials has several disadvantages since chairside time is required to fabricate the impression, an individual one is required for each film position, storage is needed for each patient's set of impressions and time is taken for cleaning and retrieval. Perhaps the biggest problem is the long term success of this method. Schmidt et al (1988) found in a subtraction radiography study of 106 pairs of bitewing films that many of the film images made 1 year after the initial examination could not be subtracted due to deterioration of the impressions, tooth loss, tooth movement or new restorations. They recommended that relocatable impressions should not form the basis for standardising film holder positions.

Rigid collimator tube coupling has been used by Grondahl et al (1987); McHenry et al (1987) and Pitts (1983b) in order to reduce positioning errors. However, this author has found that precisely positioning a

heavy X-ray head to dock with a reference ring attached to a patient is a difficult procedure.

Despite the numerous methods of attempting positional standardization, there is no agreed method for assessing film holder performance. Moystad and Larheim (1989) commented that most studies have examined the frequency of approximal surface overlaps but not the reproducibility of positioning. Pitts (1989) used half enamel thicknesses as a unit for assessing change of overlapping for reproducibility testing. With alterations as small as 2.5 ^{o} of the X-ray beam in the horizontal plane producing overlap changes of 0.1 mm (McDonald 1984), accurate measurements are required to test for positioning reproducibility and no papers have reported measurements to this accuracy for serial films.

In summary, there are no simple quick devices for producing standardized film positioning which have been shown to have a high reproducibility. Approximal overlap changes of half thicknesses of enamel (0.5 mm to 0.6 mm) could represent as much as a 15 ^{o} horizontal beam angle change between serial films and more accurate measurements are required to test for reproducibility. In Appendix V the design of a stentless repositionable film holder is reported together with results from a small pilot study.

4.4 Validity of intra-oral images

From the preceding sections 4.3.2.1 to 4.3.3 it is apparent that

several factors either singly or in combination may affect the validity of radiographic images.

Estimates of film density measurement errors have been reported as ± 0.25 mm aluminium equivalents [AE] (Clark et al 1990), ± 0.30 mm AE (Verrier et al 1989) and ± 0.40 mm AE (Plotnick et al 1970). Verrier et al (1989) stated that 0.3 mm AE represents 5% to 10% of the bone mass of an average interdental crest. The validity of using reference wedges at all for estimating density changes has been questioned by Webber et al (1989). It was shown that beam hardening effects (where low energy X-rays are preferentially absorbed by tissues from the multi-spectral beam) can by themselves produce mass estimation errors of up to 7%.

There are few papers describing the validity of alveolar crest height measurements. Stoner (1972) reported that 87.5% of direct CEJ to alveolar crest margin measurements agreed ± 1 mm with radiographic measurements. Albandar (1989) reported that similar measurements underestimated direct measurements on 278 sites on dry skulls by 0.40 mm ± 0.85 mm.

Caries validation has been discussed in section 3.5.4. Unlike alveolar crest margin changes where bone structure is lost, early precavitation lesions are regions only of demineralization. Unless a specific density loss is defined, it is difficult to test the validity of radiolucencies. The validity of radiolucencies to represent in vitro approximal caries are experimentally investigated in Appendix IV.

4.5 Measurement of alveolar bone level

Various methods have been devised for measuring alveolar crest margin changes but in general they can be divided into i) direct measurement of the CEJ to alveolar crest margin distance or ii) a proportional method where the height of the alveolar crest margin is expressed as a percentage of the root length (Schei et al 1959) or the tooth length (Bjorn et al 1969).

Proportional measuring methods arose as an attempt to cope with the variations of film position and X-ray angulation when the bisecting angle technique was routinely used. These variations produced distortions of the images which made comparisons of absolute measurements between serial films unreliable. Albandar and Abbas (1986b) compared the results of measurements made by the direct method with those from the Schei and Bjorn proportional ruler techniques. It was found that the direct method was preferred due to the higher proportion of sites which were visible. Kaimenyi and Ashley (1988) compared measurements made from a proportional-based ruler method against linear measurements made between the CEJ and alveolar crest margin. The authors concluded that the proportional method was invalid due to 50% of sites which scored zero having a CEJ to alveolar crest margin distance of >= 2.0 mm.

4.6 Computer-based diagnostic methods

This section will consider the essentials of image capture and conversion to digital form, practical problems of using digital imaging equipment and a review of clinical measuring systems. For periodontal disease, this will concentrate on the computer enhanced subjective subtraction method (Webber et al 1982) and for approximal caries, the objective method developed by Pitts (1984a).

4.6.1 Introduction

As has been discussed previously (section 1.3) current subjective diagnostic methods are unreliable. Computer-based methods offer the ability of numerically manipulating images either to improve their appearance for subjective viewing, as in subtraction radiography (Webber et al 1982), or for automatic objective analysis. Fully automatic image recognition is an exceedingly difficult task and occupies a great deal of research activity in the field of artificial intelligence (AI) (Hanson and Riseman 1978; Marr 1982; Gonzalez and Wintz 1987). An intermediate situation is possible where minimal initial human guidance is provided and the computer system makes the final objective measurements (Pitts 1984a).

Before a computer can operate on an image, the smoothly varying grey densities of the radiograph (analogue form of image data) must be converted into discrete grey level steps represented by numbers (digital image data). This analogue to digital (A to D) conversion of

the image is usually performed on the video signal output from a camera by a video digitization board (frame grabber) inside a computer. Once digitized, the image is stored in a special area of dual ported ramdom access memory (frame store) which can display its contents as an analogue image on a video monitor. The digital image is stored in the form of picture elements (pixels) where each pixel can have a grey range number from 0 (black) to 255 (white) . Each pixel has a finite area which divides the image commonly into 256 (horizontal) x 256 (vertical) or 512 x 512 or 768 x 575 pixels.

It is important to realize that the digitization process involves the loss of spatial and grey information. A 41 mm x 31 mm number 2 sized periapical film, which completely fills the monitor screen, captured at a resolution of 768 x 575 pixels (0.05 mm x 0.05 mm/pixel) has an effective resolution of about 6.5 lp/mm as measured by this author using a type 53 Siemens test grid. The original screenless film image had a resolving power of about 20 lp/mm and the digitization process reduced it to an equivalent intensifying screen/film combination which is a significant degredation. In addition the range of optical densities found in screenless film is usually larger than an imaging system can display. This can be seen as loss of information at the dark end of the range where thin regions of bone seen on the film cannot be distinguished from the interdental space in the digitized image. Pitts (1987) reported that camera "proximal burnout" could have been responsible for some of his false positive findings in investigating approximal enamel regions. To counteract this, alteration of the linearity value of the camera video amplifier (gamma

value) from 1.0 to 0.45 can be made to increase the sensitivity at the dark end of the range at the expense of the light grey values. However, since dental disease usually produces radiolucencies it is acceptable to compress the white end of the spectrum.

Video cameras can be separated into Vidicon or CCD types. Vidicons are cathode ray tubes where a light sensitive screen is charged by incoming light and "read" out by a scanning beam of electrons. The output signal suffers from distortions inherent to vidicon design caused by the electromagnetic scanning coils, tube face distortion, thermal electron noise from the cathode and drifting with time and temperature changes. CCD cameras do not suffer from these problems and are not expensive. As a consequence it is recommended that CCD cameras with sensor arrays of 600 x 575 or greater should be used in preference to vidicon tubes.

Video cameras can be used either with an automatic gain control (AGC) or a manual control. The operation of AGC varies from camera to camera and this author prefers manual control since the best combination of lens aperture and amplification can be chosen to reduce image noise.

The new intra-oral CCD X-ray sensors effectively remove the variables associated with film processing but do limit spatial and grey resolution compared to film (section 4.3.1.3). However, the images are immediately suitable for computer processing.

Radiographic images can be projected onto flat digital plotters where

the X, Y coordinates of image features can be recorded. This has the advantage that no image digitization degredation occurs and reliable measurements are possible (Goodson et al 1984; Fredrikson et al 1989; Table 3.3). This method is however unable to perform any image transformations.

This technical discussion has been included to show the complexities of using digital systems and that considerable experimentation is required to select the optimum operating conditions. It is unfortunate that most researchers do not seem to appreciate that the most important starting point is a high quality digital image. No amount of digital processing can replace what has been lost during the aquisition process. In a recent review of digital imaging in periodontal radiography (Bragger 1988a) none of these technical problems were discussed.

4.6.2 Approximal caries diagnosis and monitoring

Okano et al (1982) used a computer-based video method to investigate the effect of quantum noise on the detection of early approximal lesions. Unfortunately the computer simulated enamel lesions bore little resemblance to natural caries. This must cast considerable doubt on the authors' conclusions that faster imaging systems could be used in dentistry reducing patient radiation dose without loss of diagnostic information.

Grondahl et al (1982) performed a similar artificial caries experiment

with similar conclusions. It is disappointing to find that better caries models have not been used to evaluate these new computer techniques in both Okano and Grondahl's papers. The importance of realistic test models is discussed in section 8.5 .

Recently Halse et al (1990) using the image enhancement technique of digital subtraction radiography reported that in vitro, an application of 10% stannous fluoride solution increased the radiodensity of existing approximal lesions. Although the use of stannous fluoride as a contrast medium is interesting, there are potential pitfalls. If a selective permanent uptake occured within different parts of a lesion, this could mask future demineralization and remineralization changes. Further investigation is required to determine if the use of contrast agents is feasible for enhancing caries detection and monitoring.

Pitts (1984a) was the first researcher to perform a detailed investigation of the potential of computer-based image analysis for objective diagnosis and monitoring of approximal caries progression in permanent teeth. He found that during the early 1980s, the cost of video cameras, mini computers, image digitizers and frame stores decreased sufficiently that university researchers had an opportunity to use this new technology. Even so, the 64 Kbyte main memory and floppy discs used in Pitts' system would be considered today to be very modest hardware.

Pitts (1984a) used a vidicon camera as input device and multiple frame averaging to reduce the image noise which was digitized to 512 x 512

pixels and 256 grey levels. A suite of specialised Fortran image analysis programs were developed by Toltec Computers Ltd, Cambridge to investigate bitewing images irradiated and processed under standardised conditions. Each radiograph was orientated on a viewing box with the long axis of the tooth vertical to the monitor screen and enlarged to a pixel size of 0.03 mm x 0.03 mm producing 33 pixels per mm of enamel. A protocol was devised for a human operator to place a white pixel box around an area of the monitor screen. This included the approximal surface, dentine region just deep to the ADJ and areas of normal enamel occlusal and cervical to an approximal region of interest.

Three versions of software were developed and the final one used a multi-stage approach. First the computer searched horizontally along each line of pixels from dentine to the enamel surface. The program was looking for a sharp increase in grey values indicating the ADJ and then for a sharp drop representing the enamel surface and both features where automatically marked by white pixels. This produced a vertical line for the ADJ and another for the enamel surface. The next stage was for the program to traverse along a number of vertical paths equidistant from the enamel surface applying high and low grey filters to remove noise and low frequency spatial variations. The latter was needed since the gradual reduction in enamel bulk from the contact region to the CEJ superimposed a grey level reduction which could mask subtle radiolucencies. After the filtering and smoothing were completed, an offset threshold was applied to determine where the boundary of a radiolucency could be marked with white pixels. A choice

of outputs were available including lesion depth as a percentage of enamel thickness, depth in mm, area in mm^2 and density in arbritary units from a step wedge or relative to adjacent sound enamel. Six minutes were required to measure one lesion plus another 3 minutes if an outline plot was required.

The final version of the software was validated using 24 posterior permanent teeth which were divided into 13 macroscopically carious and 11 sound (Pitts and Renson 1986). Six of the lesions were cavitated providing a test sample of sound teeth, early enamel precavitated lesions and small cavities. All the teeth were histologically examined and 11 were caries free and 7 of the lesions were confined to enamel but not reaching the ADJ.

Triple determinations (readings) were made using the image analyser system (IAS) and an analysis of the mean depth % from the third version of software is shown in Table 4.2. The overall diagnostic accuracy was 83% but this reduced to 78% if the dentine lesions were excluded.

The reproducibility of the triple determinations for the depth % was expressed as the "average" standard error of the mean which was 5.2%. This compares very favourably with measurements by eye which are unreliable even at the 33% level (Mileman et al 1983).

Table 4.2 Diagnostic performance of an image analysis system - calculated from data in Pitts and Renson (1986).

Sample	Sensitivity	Specificity	PV+	PV-	Accuracy
n	%	%	%	%	%
24	92	72	80	89	83
18*	86	73	67	89	78

Key: PV+, PV- = positive and negative predictive values.

* = sample including sound and enamel only lesions.

A comparison was made by Pitts (1987) between the diagnostic performance of the IAS and 10 observers using in vitro radiographs from 20 macroscopically sound and 20 macroscopically carious approximal surfaces. The teeth were histologically examined to determine their true state. The overall diagnostic performance of the IAS was 73% which was slightly better than the average observer at 66%. The IAS was more sensitive (78%) than the visual observers (50%) but the IAS specificity was lower (62%) than the clinicians (95%). Pitts (1987) felt this was due to the high sensitivity of the IAS detecting small radiopaque islets (Pitts 1984c), enamel maturation defects (Pitts and Renson 1986) and camera "proximal burnout" (section 4.6.1).

A more difficult test of the IAS was devised by measuring 40 approximal radiolucencies where there was overlapping of the surfaces by up to 50% of the enamel cap (Pitts 1986). The test retest

correlations for the overlapped surfaces were highly reproducible at 0.83, 0.86, 0.92 and 0.91 for triple determinations of depth %, depth mm, area ^{2} and density (Pitts 1986). The significance of this is that often in surveys the protocol excludes overlapping surfaces. As a result a high proportion of potential disease sites can be lost increasing the numbers of subjects required to prove the efficacy of a therapeutic agent. As Sewerin (1981) and McDonald (1984) have shown, overlapping is very common in radiographs and an accurate measuring method which can read overlapping surfaces is an important development.

Later Pitts and Renson (1987) used the IAS to monitor the behaviour of 100 posterior approximal carious lesions from 2 studies using serial bitewings. The first group were 11- to 13-year olds in a 1960 study while the second group were 20- year olds in 1980. The IAS discovered inter-group differences and demonstrated more lesion regression in the older group. One reservation expressed by Pitts and Renson (1987) was the possibility that small variations in irradiation geometry could give rise to false caries changes at this level of accuracy.

4.6.3 Summary

Pitts (1984a) has designed the first IAS which is clinically useful and tested it realistically in vitro with histologically examined natural carious lesions. It has been extensively evaluated for reliability using radiographs from clinical trials. The diagnostic accuracy of the IAS is slightly better than the average human

observer. The sensitivity is significantly higher than a clinician and although the specificity is lower this should not matter, provided standardised irradiation geometry is maintained between serial films. This will prevent false image change of non-carious radiolucencies. Since the IAS is required to monitor as well as diagnose lesions, a high reliability is needed which the testing has shown it possesses. The combination of high sensitivity and reliability means that if today's philosophy of "wait and see" is followed then clinicians should not be concerned by false positives since with a standardised technique they will not change and can be ignored. However a method of detecting irradiation geometry change, possibly through measuring the extent of surface overlapping, should be added to increase confidence that any image changes detected are valid. The Pitts' method is a valuable research tool but the initial manual selection of the regions of interest is a lengthy procedure, requiring 60 minutes or more per film. If a way can be found to automate this selection process, it would increase the chance of the technique being used routinely in general practice.

4.6.4 Alveolar crest diagnosis and monitoring

This part of the review will concentrate mainly on methods for measuring density changes and in particular the use of the digital subtraction radiography method (DSR) for enhancing images for subjective and objective evaluation. Since 1982, the DSR technique has been investigated by many researchers as a potential new method for accurately detecting very early changes in alveolar crest margins.

Indeed, some workers are even suggesting it will become a routine clinical tool (Bragger 1988a).

The radiographic diagnosis of periodontal disease can be attempted by a number of different approaches:-

Linear measurements

A change in the distance between the CEJ to alveolar crest margin distance can indicate horizontal bone loss and existing methods have been already reviewed (section 3.6.4.1). Although errors as low as 0.02 mm have been reported for non-digital techniques, no digital imaging method has achieved the suggested reliability of SD 0.15 mm (section 2.4.8) for all possible sites of radiographic interest.

Spatial frequency analysis

Analysis of spatial frequencies of alveolar bone has shown that characteristic frequencies can be found using Fast Fourier Transforms to recognise different trabecular bone patterns (Ishizuka 1981; Sato 1986). Although this is a promising area of research it does not seem to have stimulated much activity.

Density changes

The ability to accurately detect sub-crestal changes is very important as there is some evidence to suggest that these might be the earliest indicators of bone loss (section 3.6.4.3). Current density

measuring can be divided into either densitometer or DSR methods.

4.6.4.1 Densitometric estimations

Payot et al (1987a) developed a hybrid densitometer and digital system. The densitometer provided analogue output from a motorized scan of a radiograph driven by a computer. Interactive digital imaging methods were used to select the portion of the film for scanning and an A to D convertor allowed digital manipulation of the densitometer output. An aluminium wedge was used for density comparisons between films.

A repositionable periapical film holder incorporating occlusal stents and rigid tube coupling were needed to produce superimposable serial films of the lower molar regions. Ten patients had a periapical film exposed and the view repeated 2 months later. Repositioning of the films were checked by linear measurements made between the roots of teeth but the reliability was not reported. Areas under the curves for aluminium equivalents (AE) made from density tracings on the same films were very reliable with a coefficient of variation of 0.02%. No in vitro validation was performed.

The method was tested on 16 patients with 38 lower molar furcation involvements, who received treatment and 7 control patients with 15 furcations who were untreated (Payot et al 1987b). The alveolar bone for reporting purposes was divided into a superficial 2 mm band of alveolar crest margin and an adjacent deeper 2 mm band.

By 2 months after surgery a density drop was measured in the superficial band of 7% ± 1% of the area under the curve of AE and at 12 months this loss had been replaced by a net gain. In contrast no change was found in the deeper bone. In the control group an almost linear loss occurred of 2.5% of density per year for 2 years in the superficial region but no change was found in the deeper bone. No significant changes in probing depths were found in any of the patients during the study.

Verrier et al (1989) recently developed a computer-based method using a CCD camera and an aluminium step wedge to calculate AE densities for the alveolar crest margin region. Using dry skulls the accuracy of the density measurements were assessed as ± 0.3 mm AE or 5% to 10% of interdental bone mass. The lower accuracy of this method compared to Payot et al (1987a) was probably due to the CCD camera which is less accurate for measuring optical densities than a densitometer.

In conclusion, Payot et al (1987a; 1987b) have developed and clinically tested an objective densitometric method which is able to detect small amounts of bone density change in the superficial 2 mm of the alveolar crest margin of lower molar furcations. It requires very difficult irradiation geometry standardization and the measuring technique must be lengthy to perform. Nevertheless this method can provide very useful research information from a limited number of patients.

4.6.4.2 Digital subtraction radiography

Photographic methods in medical radiology have been used for subtracting pre- and post-injection radiographs of contrast media to enhance the visibility of regions of interest (Bragger 1988a). Photographic subtraction without the use of contrast media has also been used in dentistry (Jansen et al 1989) but since the early 1980s (Webber et al 1982) digital subtraction radiography (DSR) has been intensively investigated as a new research technique for studying alveolar bone changes.

DSR has been examined for objectively estimating density changes (Braegger et al 1987, 1989) and to enhance images for subjective assessment of bone changes (Webber et al 1982; Grondahl et al 1988). [Note: the names Bragger and Braegger are correctly copied from the references and appear to be the same person].

The problem in detecting by eye small amounts of change at the alveolar crest margin or subcrestally is that these image regions are complex and confusing. The basis of the subtraction method is to produce standardized serial films with no variation in exposure, irradiation geometry or chemical processing. A subsequent film is digitally subtracted from an original or previous film and providing perfect standardization has been achieved, all the anatomical structures will be cancelled in the subtraction image. Ideally a "ground glass" appearance covers the successfully subtracted background region revealing the areas of biological change as clearly

visible dark or light patches. Unfortunately this ideal subtracted image is rarely achieved. A detailed description of the method follows, together with a review of its major limitations and attempts to overcome them.

The DSR method requires an initial radiograph to be input via a video camera and stored as a digital image in a computer. A subsequent radiograph is placed beneath a video camera and the position of the film altered until it superimposes as closely as possible onto the image of the original radiograph in the computer monitor. The subsequent radiograph is then digitized and stored in the computer.

By converting the pixel grey levels of the subsequent image to negative values and mathematically adding them to the original image a subtraction image is formed. Wherever the grey values in the 2 digitized radiographic images were equal, a zero value pixel will be found in the subtracted image. However, the majority of pixels will not have cancelled completely and having either a positive or a negative value. Since grey levels can only have positive values for displaying images, an offset value of 127 is added to every pixel. This transforms a pixel with zero value to a middle grey of 127. Any pixels with a negative subtraction value (indicating radiodensity loss between serial images) will be transformed to a darker grey below level 127 and a positive subtraction value (radiodensity gain) will be a lighter grey above 127. Hence the resulting subtraction image is generally mid-range grey but with light and dark regions indicating net subtraction gain or loss.

Changes in exposure, irradiation geometry, film emulsion and processing, viewing box illumination, camera setting and digitization noise will unfortunately produce false non-biological subtraction values. These false changes are very difficult to prevent and are now reviewed.

Irradiation geometry change

Experiments have been performed to investigate the alteration of subtraction images due to variation of the X-ray beam direction.

Grondahl et al (1984) drilled sixteen 1 mm^3 holes in interdental alveolar crest margin bone of 5 dry skulls after making an initial radiograph to record the original bone state. A series of subsequent radiographs were made at 3 ^{o} intervals over the range $\pm$ 6 ^{o} in the X and Y planes without artificial cheek scatter. By subtracting the original image from each of the subsequent images it was possible to create subtraction images with a known irradiation geometry. The subtraction images made with a 6 ^{o} angular difference were judged subjectively to be too noisy while those with a 3 ^{o} variation were acceptable. It was recommended that angular variation between serial films should be <= 3 ^{o} . Grondahl et al (1984) compared the diagnosis by 10 clinicians viewing the conventional films against DSR images from the same films of the in vitro lesions using the receiver operating curve method. Under these ideal experimental conditions of no soft tissue scatter and a single axis point for rotating the X-ray beam, the DSR method was significantly better than traditional viewing

with 1 mm^3 deep cortical holes being identified.

Ruttiman et al (1981) also using dry mandibles and controlled angular variation of the X-ray beam investigated the standard deviation (SD) of grey levels about the mean in a subtracted image as an objective measure of residual structured noise. It was found that providing the angular change was <= $\pm 2^{o}$ the residual noise was less than the anatomical differences allowing the experimental lesions to be seen.

Contrast correction

Ruttimann et al (1981) investigated contrast correction between serial films with an exposure ratio of 0.75 and 0.50 using a quadratic contrast matching transformation. It was found that the mean SD of the grey level distribution (an indication of subtraction noise) could be reduced by a factor of about 5 using the contrast correction transformation.

Ruttimannn et al (1986) introduced a subsequent method for contrast correction between serial films using the cummulative sum of the grey level histograms of the images to be subtracted. This was a histogram equalization method using rebinning of grey levels (Gonzalez and Wintz 1987) and provided an improved contrast correction compared to their earlier paper (Ruttimann et al 1981).

These papers demonstrate that the DSR technique is susceptible to angular irradiation geometry changes of the X-ray beam greater than

2-3 ^{o} but that exposure variation can to some extent be corrected.

In vitro detection of bony holes

Grondahl et al (1988) investigated the detectability of artificial marginal bone lesions by drilling holes with a round bur of 0.85 mm diameter into the buccal part of the alveolar crest margin adjacent to the mesial surface of the first molar in 6 dry human mandibles. A series of radiographs were made under strictly controlled conditions where the bucco-lingual extent of the lesion hole was increased by 0.5 mm increments. Ten dentists were asked to identify the lesions from conventional and DSR images (same evaluation method as Grondahl et 1984) and it was found that 0.5 mm deep holes could be seen with DSR but 1.5 mm were the smallest holes seen using conventional images.

Jansen et al (1989) performed a similar experiment but with a mandible enclosed in polymethylmethacrylate to simulate soft tissue X-ray scatter. However, they used holes of 1.5 mm constant depth and varied the diameter from 0.3 mm to 1.4 mm in steps of 0.1 mm, effectively drilling cylinders into the alveolar crest margin. It was reported that using a quantitative method of aluminium equivalents the DSR method detected 0.3 mm diameter holes but with conventional films the size increased to 0.83 mm before detection occurred.

These 2 papers show that under laboratory conditions small bony holes can be detected better by DSR than by conventional film examination. However, there is an implicit assumption by these investigators (and

others) that small round regular highly defined holes truly represent early bone changes and yet there is no evidence in the literature to support this view. Diagnostic methods require realistic models to test their performance and symmetrical drilled holes are unlikely to be an ideal model.

CADIA

Computer assisted densitometric image analysis (CADIA) is a variation of the DSR technique for making densitometric estimations of change between films (Braegger et al 1987, 1988b, 1988c, 1989). The method uses contrast correction with copper reference wedges for histogram equalization, operator selected regions of interest (ROI) and averaging of 2 x 2 groups of pixels in the ROI. The positive and negative values of the pixel groups are added together to produce a Net-CADIA value which is used to represent the overall density changes in the ROI.

There is however some doubt as to the accuracy of the CADIA technique. Braegger et al (1987) in their initial clinical evaluation of the CADIA method reported that radiographs were made before and immediately after surgery in 2 groups of 22 and 23 surgical sites. Each group had an equal number of untreated matching control sites in the opposite quadrant of the mouth. In group one 9% of the control sites had false positive (FP) and 27% false negative (FN) density changes as reported by the CADIA method. Group two had 9% FP and 26% FN CADIA values. The control and the treatment groups were compared by

statistical tests but no results were reported. With 36% of the control results from the validating tests being reported as either FP or FN, serious doubts must arise regarding the accuracy of this technique.

Methodological errors

McHenry et al (1987) reported on different methodological errors they had encountered with evaluation of clinical radiographs using the DSR technique. Under ideal conditions a classical ground glass background would be formed in a successfully subtracted image. However, they found this was infrequent and usually only a proportion of the available sites in a subtracted image could be evaluated due to noise. McHenry et al (1987) demonstrated how a successfully subtracted ground glass image with no "diseased" regions could, by misalignment of a radiograph prior to capture by the video camera, produce an image with false alveolar crest margin bone loss. This was not a detailed study and the potential importance of manual film misalignment errors on the accuracy of the DSR technique was not investigated.

Hausemann et al (1988) reported that 42% of 887 alveolar crest margin sites were excluded from a study either because the subtraction images were uninterpretable or did not yield the same interpretation on duplicate analyses.

Janssen and van Aken (1989) reported that in vitro studies using a dry mandible with aluminium cylinders of known volume showed that the DSR

method underestimated aluminium equivalent volume by 10% at 50 kVp and overestimated it by 30% at 90 kVp. In clinical studies from the same paper they commented that variations of saliva levels and soft tissue position of the cheek may alter subtraction images.

4.6.5 Summary

Digital video methods capable of accurate (SD 0.15 mm) measurements of CEJ to alveolar crest margin distances for all available sites are not available. However, radiographs magnified and projected onto a digital plotter can achieve accurate measurements for the majority of sites.

A hybrid densitometer and digital imaging system for measuring furcation margin density changes has been shown to be very reliable on clinical radiographs but has not been validated in vitro.

The DSR method under rigorous laboratory conditions can facilitate the detection of small well defined bony holes significantly better than conventional images. However, the ability to achieve the required level of standardization for all aspects of the X-ray image production process raises serious doubts as to the clinical usefulness of this technique. Further technical evaluation of the DSR technique is required as it seems very premature to think of this as a proven diagnostic tool.

4.7 Overall review summary and recommendations

The current principal prognostic and diagnostic tests for caries and the periodontal diseases have been reviewed in chapters 3 and 4. No accurate prognostic tests exist and the traditional methods of visual observation and use of probes are unreliable methods for diagnosis of caries and periodontal diseases. The most accurate method for diagnosing and monitoring early posterior alveolar crest margin bone changes and approximal caries is bitewing radiography. Radiography is able to diagnose one third of occlusal caries which have escaped visual diagnosis. Electrical resistance methods show promise in diagnosing and possibly monitoring early occlusal caries.

The effect of irradiation geometry changes in the diagnosis of early alveolar bone loss has been shown to be important by in vitro DSR studies. However, no detailed investigation has been made of the effect of geometry changes on the diagnosis of early approximal precavitation lesions and this should be performed (Appendix IV).

Standardized film positioning is important to maintain the validity of serial films. A stentless repositionable film holder suitable for general practice is required.

The DSR method as the major recent research method for investigating alveolar bone changes has numerous methodological problems which should be further investigated.

An accurate, simple to use, general purpose method suitable for making very reliable linear measurements of radiographic features would be a useful tool for clinical research. It should have a reliability of SD 0.15 mm and be capable of measuring tooth and bone features together with an automatic estimate of the reliability of each measurement made.

The current accurate and objective radiographic methods for monitoring approximal caries (Pitts 1984a) and furcation alveolar crest margins (Payot et al 1987a) are very lengthy laboratory techniques involving initial human operator selection of regions of interest. It is desirable that objective disease monitoring should be performed in general practice but either completely automatic or minimal operator interaction systems will be required to make this feasible. A study is required to investigate the feasibility of automating image analysis to allow objective measurements to be made.

The following chapters 5, 6, 7 and appendices IV, V contain experiments designed to investigate and provide tools for the problems revealed by this review of the literature.

Chapter 5 The development of a computer-assisted method for making very reliable linear measurements from radiographs.

5.1 Introduction

Measurement is an integral part of dental research and yet there is no accurate general purpose dental digital imaging system available for this purpose (sections 3.6.4.1, 4.6). Such a system should ideally be capable of making linear radiographic measurements between any 2 available anatomic sites with at least a 90% confidence in achieving a reliability of standard deviation (SD) 0.15 mm for repeated measurements (sections 2.3.5, 2.4.8). Some measuring methods have been developed which have achieved a reliability of SD 0.16 mm or better on measuring alveolar bone changes (Goodson et al 1984; Al-Kufaishi et al 1984; Fredrikson et al 1989). However, the images were not digitally stored, unsharp areas were unreliable to measure and not all types of anatomical structures could be selected for measuring. A tool for easy, reliable and confident measuring between the cement-enamel junction (CEJ) and alveolar crest margin, the width of the periodontal ligament space, trabecular rod size, carious lesion depths and approximal surface overlap would be of great benefit for detecting early signs of dental disease.

Wouters et al (1988) demonstrated that a digital plotter can make reliable measurements of SD 0.02 mm from an enlarged highly defined reference scale. However, when the same system was applied to clinical radiographs with less sharply defined image boundaries, the human

operator variation in selecting the measurement sites reduced the reliability to SD 0.49 mm.

Hence the key weakness in any computer-assisted measuring method is the human operator, since unsharp features will be measured with a lower reliability than sharp ones. This is likely to lead to different confidence values in the reliability of the measurements made by a single operator at different sites in the same radiograph. The normal practice in dental studies to overcome this problem is to resample 10% of the total and estimate a reliability coefficient, such as a weighted Cohen's kappa (Bulman and Osborn 1989). As with all such estimates the reliability of a measurement for any given site is unknown. The ideal situation would be to have a reliability value for every site and a confidence value for changes measured between serial films.

The aim of this work was to devise a digital image method for i) reducing operator error in selecting reference points, ii) automatically calculate the measurement reliability for every site and iii) provide a 90% confidence estimate for measured change between the same sites in serial films.

5.2 Materials and Methods

Since the major problem is the constant identification by the operator of the same reference site, it was decided to design a method using a stored region of interest (ROI) from the image containing the

anatomical sites, displaying the previously selected reference points as white pixels.

The optical equipment used was composed of an intra-oral film carrier for a number 2 sized film, backlit by an X-ray viewing box, which was placed beneath a CCD video camera (Philips LDH 066, Cambridge). The camera had a sensor array of 604 (H) x 576 (V) pixels with a manual gain amplifier set to a gamma of 0.45 to boost the dark grey sensitivity. A set of lens extension rings was used so that the whole of the film filled the monitor screen.

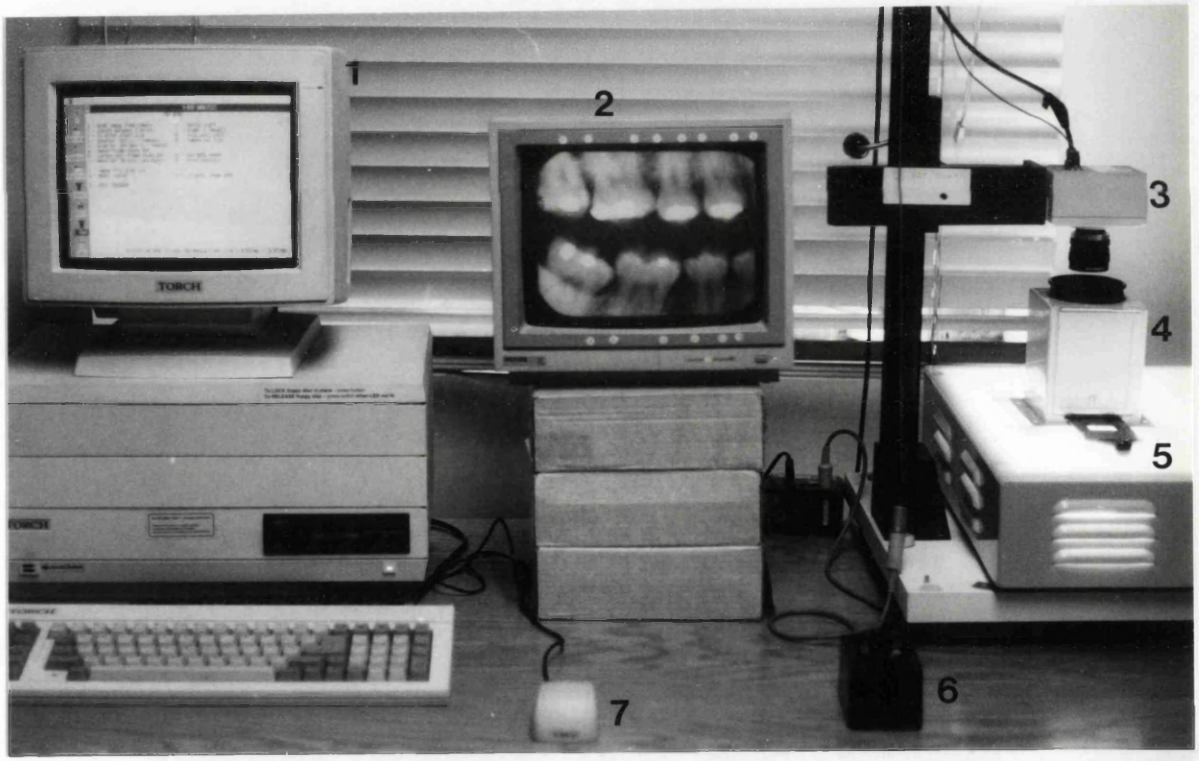


Figure 5.1 Radiographic image analysis equipment. 1= Image processing work station, 2= Monochrome image monitor, 3= CCD camera, 4= Film carrier light box, 5= Back illumination X-ray viewer, 6= Manual control of camera amplifier and 7= Mouse.

The analogue output from the camera was connected to a Torch XXX Unix workstation (Cambridge) with a Primagraphics (Cambridge) VVI7 frame digitizer and VFS8 frame store (Figure 5.1). These provided a digital image of 768 (H) x 575 (V) x 7 bits, with a grey range of 0 to 127 levels output as 0 to 255 in steps of 2 grey levels. Each image pixel represented a region of approximately 0.05 mm by 0.05 mm on the illuminated radiograph and the calibration process is described below. The mean image and standard deviation (SD) of the digitization noise was 188 $\pm$ 2.5 grey levels (approximately 1% of the 256 grey range) calculated by sampling identical points in 30 images captured from the same radiograph in 4 seconds.

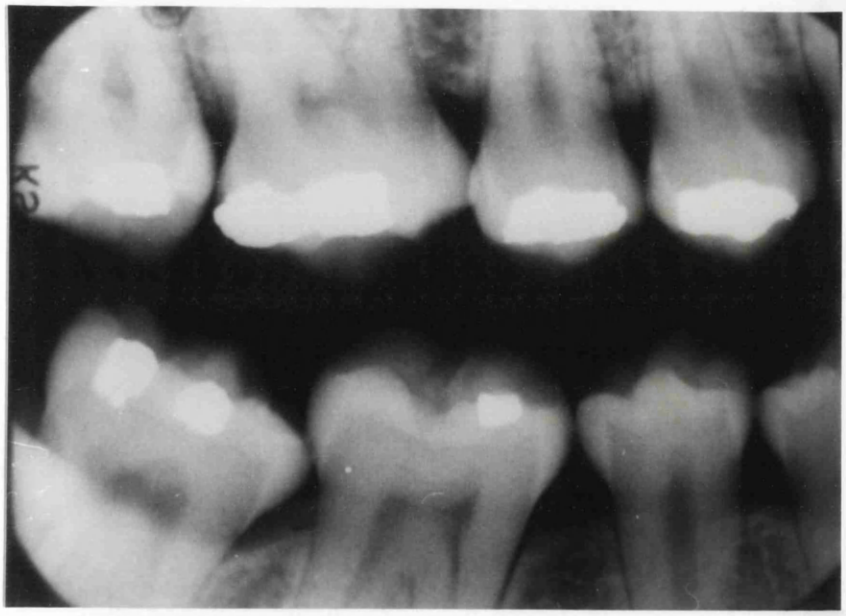


Figure 5.2 Reference digital radiographic image viewed on a monitor. Magnification x6.

Under "C" software written by the author, a bitewing radiograph was digitized and displayed on the video monitor (Figure 5.2). Calibration was performed with a 2 cm measuring scale marked in 0.1 mm units and printed on a glass graticule (Biorad, Hemel Hempstead) which was placed flat on top of the film and the combination digitized. A mouse controlled cursor was placed over the beginning and end of the scale to calculate the pixel size in the X direction. This was performed twice to calculate the mean value. The whole process was repeated after the scale was orientated for the Y axis.

The image cursor was specially designed to cover the minimum of the image with one central target pixel surrounded at a distance by groups of 5 pixels forming the corners of a virtual box. Cursors with 2 central pixels or a more obvious enclosing box of pixels were found to prevent identification of small features.

To commence the measuring process, the operator informed the computer that 7 rectangular regions of interest (ROI) were required. Each ROI was a preset area of approximately 7.5 mm x 7.5 mm, sufficient to cover the mesial and distal CEJ to alveolar crest margin regions of adjacent teeth or approximal regions. The program automatically requested the descriptions of the 7 regions to be entered for subsequent operator guidance.

The measuring process for a ROI began by placing the cursor over the required CEJ and the mouse button clicked to record the position. The cursor was moved to the alveolar crest margin and the coordinate of

the required point again recorded with the mouse button. The procedure was repeated for the adjacent CEJ and alveolar crest margin with the calibrated measurements being stored to disc. In addition the computer stored the ROI as a rectangular portion of the image including the 4 reference points marked as white pixels.

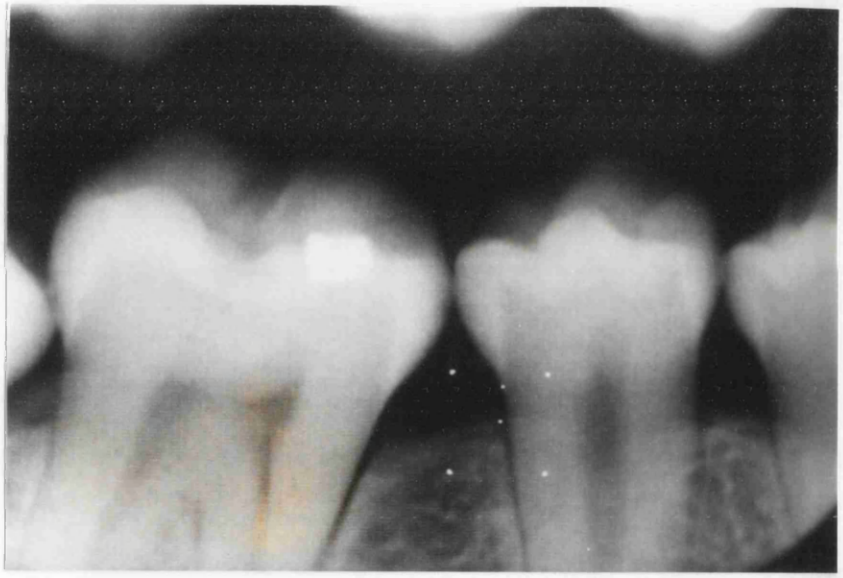


Figure 5.3 Image cursor. The centre of the cursor is shown by the white pixel over the most coronal portion of the cribriform plate forming the peridontal ligament space distal to tooth 45. Four groups of white pixels are placed symmetrically about the small single central pixel to aid identifying it. The single white pixel over the distal CEJ of tooth 45 shows this reference point has already been selected.

When the operator chose to repeat the measurements, the computer automatically displayed the stored ROI with the white reference sites, close to but not obscuring the area previously measured (Figure 5.4). This visually reminded the operator of the exact reference point previously chosen, reducing the chance of picking an incorrect site. The program prompted the operator to repeat the measurements and when these were completed, a fresh ROI was stored.

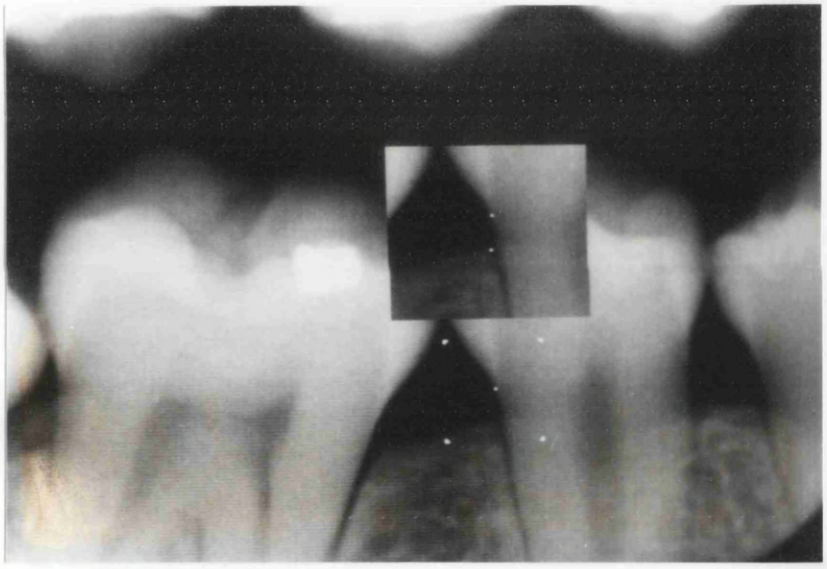


Figure 5.4 Stored region of interest (ROI) displayed over digital image. The previously selected CEJ and alveolar crest margin reference points can be seen as white pixels in the rectangular ROI. The image cursor has been placed, by the operator, over the same CEJ region guided by the ROI.

The computer automatically calculated for every site, the average distance of the initial and repeat readings as well as the measurement

error which was the difference of the readings. When all the sites had been measured twice, a subsequent serial film was digitized. The computer prompted the operator to make initial measurements on the second image by displaying stored ROI from the previous image. Hence positional guidance from the first image is superimposed onto the second image and the sites are measured as before. The generation of stored ROI is shown diagramatically in Figure 5.5.

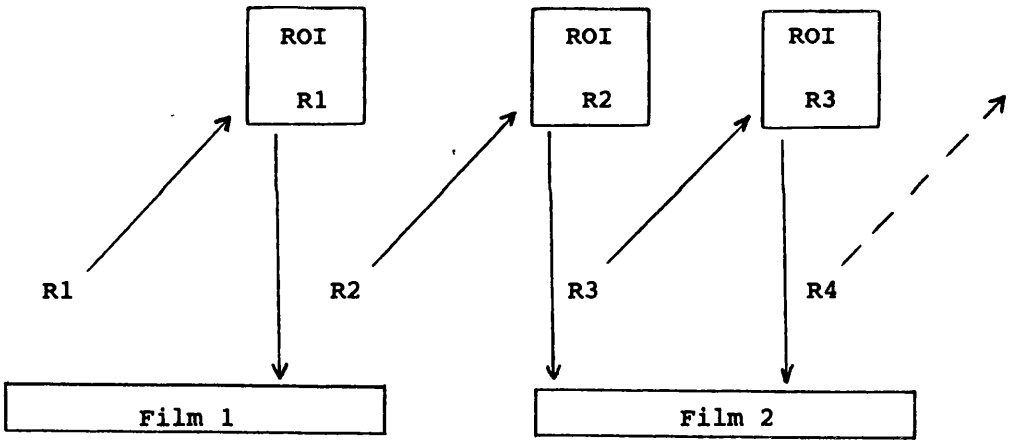


Figure 5.5 Relationship between sequence of measurement readings, stored regions of interest and film sequence.
Key: ROI= stored regions of interest, Rn= measurement reading

When the sites had been measured twice on the second film, the computer automatically calculated the average measurement error for

the readings from both films, the distance change measured between both films and the confidence value attached to the measured change. This last value is calculated by multiplying the average of the measurement errors, from a single site measured on both films, by the value 3.2. The resultant value provides an error threshold which if exceeded by the measured change in distance between films, has a greater than 90% confidence that the change is true and not a measurement error (Acton 1959). If the 90% confidence level is exceeded then the computer notes this on a printout (Figure 5.6). A fuller explanation of the sequence of measurements and calculation of the confidence value is contained in Appendix II.

```
Wed May 16 11:27:22 1990

Lower right 6 mesial (46)

Film 1: 1st reading  cej-crest distance = 1.15 mm
        2nd reading                    = 1.05 mm
        average distance               = 1.10 mm

        reading error                  = 0.10 mm

Film 2: 1st reading  cej-crest distance = 2.09 mm
        2nd reading                    = 2.04 mm
        average distance               = 2.07 mm

        reading error                  = 0.05 mm

        distance change between films  = 0.97 mm

        90% reliability threshold is
        change > (0.10 * 3.2)          = 0.32 mm

        distance change > threshold:  CEJ-CREST DISTANCE CHANGE RELIABLE
```

Figure 5.6 Printout of change, with confidence estimate, for CEJ to crest distance measured in two serial bitewing images.

In practice, approximately 15 minutes were required to measure 14 CEJ to alveolar crest margin distances twice in 2 serial bitewing films plus an additional 5 minutes for disc storage and printing out the results.

5.3 Testing of the method

The method was tested by 28 examiners of whom 12 were "experts" and 16 were Dental Public Health postgraduate students. A standard image (Figure 5.2) was chosen to represent an image of average viewing appearance. Of the 14 CEJ to alveolar crest margin sites to be measured, 3 CEJs were complex (double images or subcrestal) and 7 alveolar crests complex (both upper and lower alveolar crest margins present at same site or lack of a clear periodontal ligament space). Only 5 out of 14 sites had both a simple CEJ and crest margin with a normal appearance.

All the examiners were seated in a similar manner with the room darkened. Approximately 5 minutes of preliminary verbal and practical instructions were given in a consistent way. Each examiner was shown using diagrams and a different digitized radiograph examples of CEJs and alveolar crest margins. Where a periodontal ligament space of equal width along its superficial portion was found, the most coronal point of the cribriform plate was selected. When marginal widening of the ligament space was observed, examiners were instructed to choose the most superficial point where the space became a constant width. If a periodontal ligament space was not visible they were instructed to

pick a point where the crest margin crossed a root surface. Finally the examiners were informed that this was not a test of radiographic interpretation but of consistently selecting the same reference points.

The examiners selected a CEJ followed by a crest margin for each site until all 14 distances had been measured. One half of the examiners read the sites in a predetermined sequence and the remainder followed a computer generated random order.

After all the sites had been measured the first time, they were immediately remeasured without any form of advice or guidance. A third reading was made after a short rest but this time, a stored ROI was first automatically displayed to show the points selected by the examiner during the second reading. All the results were printed out and the stored ROI were held on a floppy disc together with all the measurement data.

A minimum period of 4 weeks elapsed before the examiners remeasured the standard image, first without and then with the stored ROI. No instructions regarding the selection of points were given although a preliminary practise with the mouse was performed. This concluded the measurements for the intra-examiner evaluation of the method. However, in order to test the inter-examiner variability, a third set of measurements were made after a short rest. In order to do this a set of ROI specially constructed by the author were used. Each ROI contained reference points which would be considered "wrong" by most

clinicians, such as a point 2 mm apical to the most superficial point of the periodontal ligament space where a constant width was found. This group of atypical points could be considered most unlikely to be chosen at random or as a result of small measurement errors by the examiners. Hence statistically they could be considered to be from a different population of points.

5.4 Statistical analysis

The measurements from the random order read sites were compared by one way analysis of variance against the values from the fixed order reading sequence. There was no significant statistical difference between the groups with probability values in the range of 0.2 to 0.6. Accordingly the results from all the 28 examiners were pooled together so that each of the 14 sites had a sample size of 28 values.

A Student's paired t test was used to test for statistically significant differences between the measurements made with and without the stored ROI. This was performed for the inter- and intra-examiner tests.

5.5 Results

The intra-examiner variation at the first visit between duplicate measurements made with and without the stored ROI, were compared using a paired t test (Table 5.1). Only one site reached the 95% probability that the 2 methods produced significantly different results. At this

site the method using the stored ROI had a SD 0.17 mm compared to SD 0.32 mm with no stored ROI. If the confidence level was reduced to 93%, 3 sites showed a difference between the methods in favour of the stored ROI. This was interpreted to mean that overall no significant statistical difference could be found at the first visit between the methods. However, after a 4 week period, 5 out of 14 sites reached the 92% to 99% confidence level. Although these values indicated a greater difference between the methods after 4 weeks it still did not reach the 95% level for the majority of sites.

In contrast, the inter-examiner comparison at 4 weeks produced a highly significant difference of greater than 99% confidence for all the sites in favour of the stored ROI method.

If absolute values are chosen to threshold the measurement variance for comparing the methods rather than the t test, a different result is obtained. With a threshold of SD 0.15 mm none of the sites examined without the stored ROI achieved this reliability either at the first or second visits. However, with the stored ROI method, 12 out of 14 sites had a SD <= 0.15 mm at the first visit and 13 out of 14 sites reached the same threshold at the second visit for the intra-examiner comparisons.

The inter-examiner variations at the second visit were larger but with a slightly increased threshold of SD <= 0.22 mm; 13 out of 14 sites achieved this reliability with the stored ROI while none achieved this without using ROI.

The 90% confidence level calculation for changes measured between sites in serial films was tested on a pair of films and found to perform correctly. The printer trace output from a single site is shown in Figure 5.6.

Table 5.1 Intra-examiner measurement variation with and without the use of stored regions of interest (ROI). [n= 28 per site]

	1st visit			2nd visit		
Site	p	no ROI (mm)	ROI (mm)	p	no ROI (mm)	ROI(mm)
1	0.07	-0.13 ± 0.28	-0.04 ± 0.15	0.23	-0.05 ± 0.30	0.02 ± 0.10
2	0.10	-0.16 ± 0.42	-0.02 ± 0.09	0.42	-0.06 ± 0.49	0.01 ± 0.11
3	0.10	0.05 ± 0.16	0.01 ± 0.10	0.42	0.06 ± 0.23	-0.02 ± 0.11
4	0.15	0.06 ± 0.28	-0.01 ± 0.11	0.79	-0.04 ± 0.31	-0.03 ± 0.14
5	0.95	-0.01 ± 0.31	-0.01 ± 0.11	0.01	-0.12 ± 0.25	0.04 ± 0.12
6	0.30	-0.09 ± 0.38	-0.03 ± 0.17	0.07	-0.10 ± 0.31	0.01 ± 0.17
7	0.06	0.02 ± 0.29	-0.07 ± 0.12	0.20	-0.09 ± 0.31	-0.01 ± 0.10
8	0.29	0.02 ± 0.32	-0.04 ± 0.15	0.08	-0.11 ± 0.32	0.01 ± 0.11
9	0.46	-0.08 ± 0.31	-0.00 ± 0.10	0.07	-0.14 ± 0.42	0.01 ± 0.09
10	0.86	-0.02 ± 0.41	0.00 ± 0.13	0.89	0.01 ± 0.64	0.02 ± 0.10
11	0.05	0.04 ± 0.32	-0.08 ± 0.17	0.28	-0.10 ± 0.46	0.00 ± 0.13
12	0.68	0.00 ± 0.31	-0.03 ± 0.13	0.90	0.03 ± 0.35	0.02 ± 0.15
13	0.67	0.00 ± 0.48	-0.04 ± 0.14	0.77	0.00 ± 0.41	0.02 ± 0.14
14	0.78	-0.08 + 0.30	-0.06 + 0.12	0.07	-0.11 + 0.36	0.03 + 0.11
Sites SD <=		0.15mm 0/14	12/14		0/14	13/14

Table 5.1 (continued) Inter-examiner measurement variation with and without the use of stored regions of interest (ROI) - second visit only.

Site	p	no ROI	ROI
		mm	mm
1	0.00	1.00 ± 0.33	-0.26 ± 0.35
2	0.00	0.93 ± 0.84	0.01 ± 0.14
3	0.00	0.25 ± 0.87	0.04 ± 0.09
4	0.00	0.85 ± 0.31	-0.03 ± 0.18
5	0.00	0.90 ± 0.35	-0.04 ± 0.08
6	0.00	0.95 ± 0.94	0.04 ± 0.16
7	0.00	0.64 ± 0.34	0.00 ± 0.10
8	0.00	1.61 ± 0.47	0.01 ± 0.17
9	0.00	1.12 ± 0.44	-0.07 ± 0.22
10	0.00	1.64 ± 0.60	-0.05 ± 0.12
11	0.00	2.24 ± 0.46	-0.12 ± 0.21
12	0.00	1.56 ± 1.02	-0.02 ± 0.15
13	0.00	0.89 ± 0.44	-0.01 ± 0.13
14	0.00	1.71 + 1.12	0.04 + 0.21
Sites SD<=		0.22mm 0/14	13/14

p= probability value from paired t test

5.6 Discussion

Using the stored ROI method a large varied group of examiners, with minimal training in using the system, were able to measure 13 out of 14 CEJ to alveolar crest margin distances to a reliability of SD 0.15 mm after 4 weeks. The inter-examiner score was the same with a reduced reliability of SD 0.22 mm. Without the stored ROI method, no site measurements reached a similar reliability. Although the inter-examiner error was slightly larger than the intra-examiner variation, the paired t test showed that the performance of the ROI method compared to the non-ROI method was highly statistically different. The intra-examiner comparison of methods was not statistically significantly different for the t test. This may change if bone loss occurs between films producing irregular or unsharp outlines which could cause difficulty in selecting reference sites.

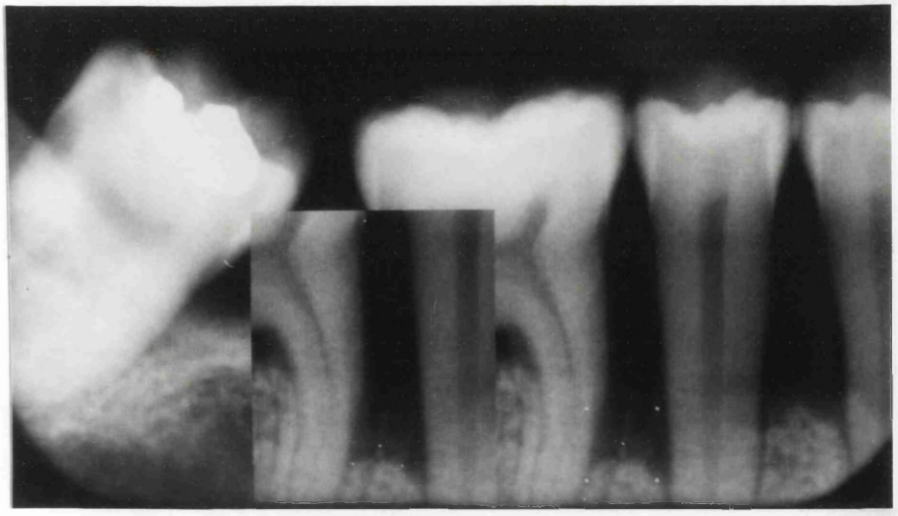


Figure 5.7 Stored ROI of irregular bony crest. Three stored reference points can be seen on alveolar crest between teeth 45,46 and the cursor is identifying the central crest point.

The results from this experiment are considerably more reliable than those reported by Hausmann et al (1989) in a preliminary report of 2 examiners using a mouse-based video system. Their best intra- and inter-examiner reliability was SD 0.25 mm and SD 0.34 mm respectively.

Although this method has been tested using CEJ and alveolar crest margin sites, it could also be used for measuring carious lesions, trabecular rod size or approximal surface overlap. In Appendix V the computer system has been used to investigate irradiation geometry changes by measuring alteration of approximal surface overlap.

5.6 Conclusions

A general purpose digital imaging system has been developed for making very reliable measurements which additionally calculates the confidence value of measured distance changes for every site examined. It has been tested by a group of examiners and in addition to periodontal measurements it can be used in caries studies and possibly research into osteoporosis.

Chapter 6 The development of a computer-based method to investigate limitations of the digital image subtraction technique in assessing alveolar bone crest changes due to misalignment errors during image capture.

6.1 Introduction

Digital subtraction radiography is a comparatively new dental diagnostic method with a literature search revealing over 47 papers being published since 1982. The majority of the research has sought to improve the early detection of alveolar bone crest changes from periodontal disease.

The basic principle of digital subtraction radiography is to take an initial standardized radiograph of a patient, followed after a time interval by a subsequent standardized radiograph. The initial film is captured by a video camera, the image digitised and stored in a computer. The subsequent image is placed under the camera and manually moved until it appears to exactly register with the initial image on the computer monitor. Once this is achieved, the subsequent image is digitised and electronically subtracted from the initial image so that all pixels, which have undergone no optical density change between the films, will have a mid grey value of 127. Pixels with grey values above 127 are interpreted as indicating tissue density increase while lower values indicate density decrease (Ruttimann et al 1981; Grondahl and Grondahl 1983).

The accuracy of the digital subtraction technique (section 4.6.4.2) to reveal changes in alveolar bone crest density is totally dependent on the production of standardized radiographic serial images (Revesz et al 1974; Grondahl and Grondahl 1983; Grondahl et al 1983). Any artificial differences, between an initial and a subsequent radiograph of the same anatomical region, will in the subtracted image produce areas of increased or decreased grey level numbers compared to the nil change 127 value. These light and dark regions could be misinterpreted as false gain or loss of bone.

Errors in standardization of radiographic images can be produced by i) fluctuation in output of photons from an X-ray source ii) alteration of the irradiation geometry iii) variation in film processing or emulsion quality and iv) misalignment of the films under a video camera prior to subtraction of the images. Variation of the X-ray beam output and film processing will alter the optical density of a radiograph. Ruttimann et al (1981; 1985) were able to achieve grey level normalization between images to reduce the effects of different optical densities from incompletely standardized radiographs. Irradiation geometry variation and the detectability of periodontal bony lesions has been investigated by Grondahl et al (1984) who showed that it was essential to reduce changes in the beam projection between films to $< \pm 3^{o}$ in the horizontal and vertical planes. In order to achieve this constant irradiation geometry, occlusal stents are frequently used with rigid attachment to the X-ray source (Rosling et al 1975; McHenry et al 1987). Even cephalostats have been used (Jeffcoat et al 1987). However, despite contrast correction and

rigorous attempts to reduce irradiation geometry variation, nearly all the published subtraction images unintentionally display false density changes in the approximal or occlusal surfaces of the teeth adjacent to the interproximal alveolar bone crest regions of interest (Webber et al 1982; Grondahl and Grondahl 1983; Grondahl et al 1983; Lurie et al 1983; McHenry et al 1987; Bragger et al 1988b; Ohki et al 1988; Schmidt et al 1988).

Artificial density changes, produced in subtracted images of the teeth, must inevitably cast doubts on the validity of the technique for interpreting nearby alveolar crest density changes as true loss or gain of bone (McHenry et al 1987). Recently an attempt has been made to automate the positioning of a subsequent image for subtraction by a tomosynthetic method (van der Stelt et al 1989a). This sophisticated technique demonstrated a reduction in subtraction errors compared with manual positioning of a radiograph for subtraction but nevertheless false density changes could still be seen in some parts of the image. It may be that misregistration of the images, which can occur during the alignment of a subsequent radiograph prior to subtraction from a previous image, is another source of potential error in the subtraction technique. McHenry et al (1987) demonstrated how a misalignment between two films, with a similar irradiation geometry, could produce an artificial shift in grey level patterns which might result in an incorrect interpretation of crestal bone change. However, no detailed investigation of this potential methodological error has been performed. The present study attempts to determine if film/image misalignment under a video camera could be a source of major error in

the subtraction technique.

6.2 Materials and Method

In order to exclude any errors which may have been due to variations of the X-ray source, irradiation geometry, film processing, light source, video camera or image digitiser, it was decided to use only a single radiograph instead of a pair of films and to create only one digital image from the radiograph. This digital image would serve as the initial image while an exact electronic copy of this would be stored in a separate area of memory (RAM) as the subsequent image. In this way one could be sure that any differences which occured in the subtracted image could only be due to image misregistration and no other factors.

A number 2 size Kodak intra-oral ultraspeed "D" clinical posterior horizontal bitewing radiograph was placed in a film carrier. The equipment and adjustments were the same as described in section 5.2.

Under "C" software written by the author, a single digital image was stored in RAM representing the whole of the original 30 by 40 mm image. This image was called the initial image and an exact electronic copy was made of this and stored in a separate area of RAM which represented the subsequent image. The degree of displacement between the initial and the subsequent image could be selected in single pixel steps of 0.05 mm in the X or Y directions or a combined diagonal X and Y displacement of 0.07 mm per pixel step. Displacement between the

images could be varied from -10X to +10X (1.00 mm total X axis displacement) and from -10Y to +10Y (1.00 mm total Y displacement) passing through zero displacement where the images should be identical. In fact much smaller displacements of 0, 2, 4 , 6 and -6 pixels were chosen for X and Y values. This produced displacements between the images of 0, 0.1 mm, 0.2 mm, 0.3 mm and -0.3 mm if only X or Y displacements were chosen and 0.14 mm, 0.28mm, 0.42 mm and -0.42 mm if both X and Y displacements were made (Table 6.1 - see Appendix III).

After the image displacement had been selected, the computer calculated the pixel shift required from the initial image to produce the subsequent image. Each subsequent pixel was subtracted from each initial pixel and the result added to an offset of 127 grey levels to ensure that areas of equal greyness in both images produced a mid range grey level in the subtracted image (Grondahl et al 1983). Approximately 50 seconds of computer time was required to produce a subtracted image.

A single number 2 size bitewing (Figure 6.1) was selected to perform an initial investigation of the effects of displacing one image relative to the other, subtracting them and then adding 127 to the final pixel values. The range of displacements chosen were -6x to +6x and -6y to +6y pixels as shown in Table 6.1.

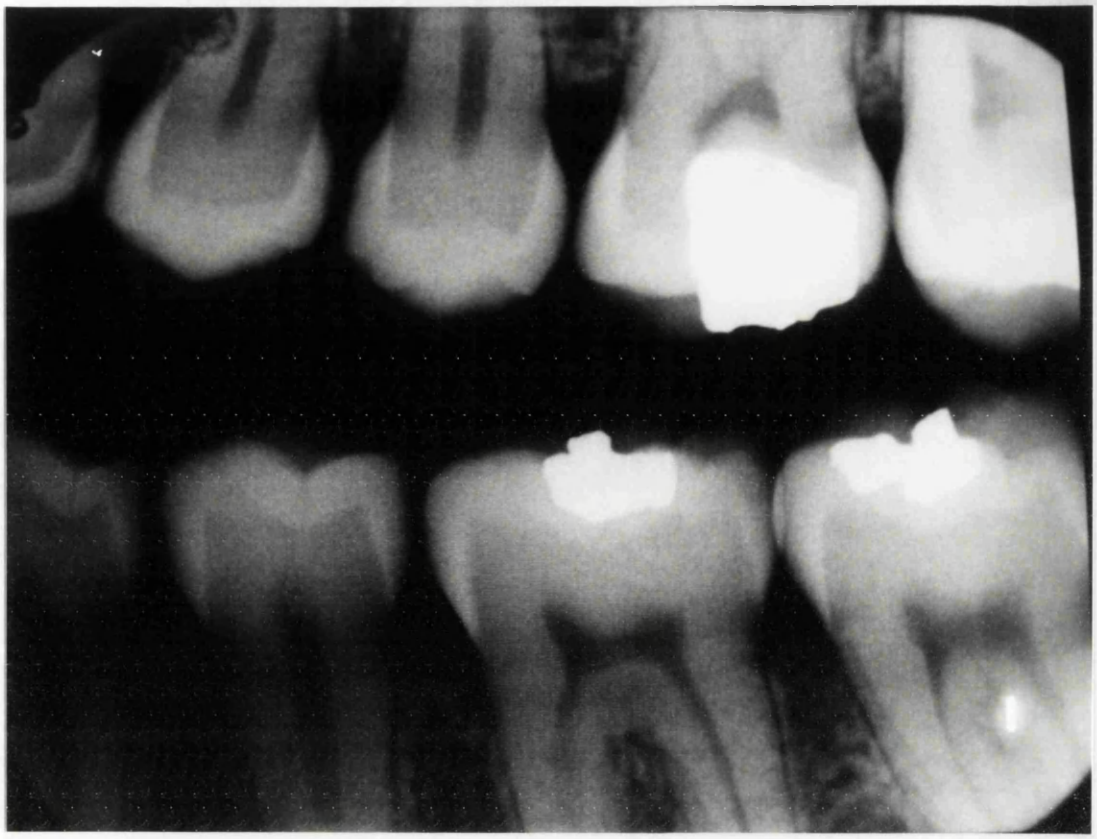


Figure 6.1 Initial digitized image of a left bitewing radiograph viewed on a computer monitor. Magnification x6. Unfortunately the optically dense regions of crestal bone between 23,24 and 34,35 are difficult to reproduce when photographing a monitor screen.

A rectangular region of 17 by 22 pixels (0.85 mm by 1.1 mm) was selected by eye on the computer monitor, midway along an interdental alveolar crest, in the initial grey level image. The grey level gradient at a tangent to the crest (occluso-apical direction) was calculated for a distance of approximately 0.75 mm along a path which passed from the dark interdental space across the lighter bone crest. The crest/interdental space boundary was found by identifying the first pixel pair with a grey level difference twice that of the variation found between pixels in the interdental space. In each

region this was performed near the left and right edges of the rectangular crest area plus the central track providing 3 gradients per region (Figure 6.2). The average of the 3 gradients was calculated to produce a single gradient value for the region. This was performed for the 7 interdental crests regions in the image (Figure 6.1).

A subtracted image with a 0.1 mm vertical displacement (X=0, Y=2) was made from the initial image and the same 17 by 22 pixel regions of the interdental crests examined. However, this time the software analysed the pixel values with regard to their spread either side of the nil change grey level value of 127. The program calculated for various ranges of grey values the total number of pixels with these values found in the 17 by 22 pixel region. It also expressed the total as a percentage of the region area and lastly a percentage cummulative total of the pixel totals for the grey range under inspection from 128 to a maximum of 255 or 125 to 0 (Table 6.2). The grey levels were divided into 7 bands on either side of the nil change 127 level. Each band represented a certain proportion of the total grey range expressed as a percentage and the total number of pixels found in each band was expressed as a percentage of the image region examined (Table 6.3). In this way a method was devised to describe both the magnitude of the grey level deviation from level 127 produced by the subtraction method and the proportion of the area of the image region affected.

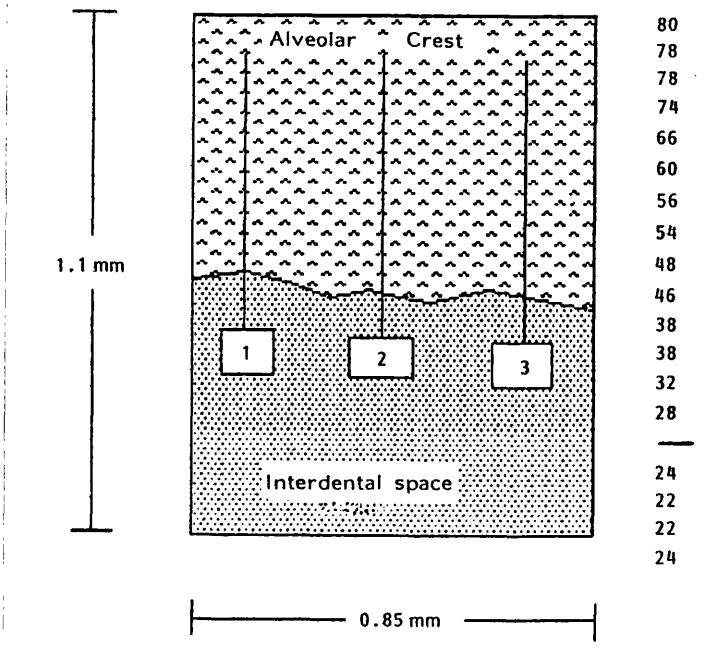


Figure 6.2 . Calculation of alveolar crest margin grey gradient. The average grey level gradient was found for an interdental alveolar bone crest by calculating the gradients from the paths marked 1,2 and 3 which were approximately 0.75 mm long. The vertical column of numbers to the right of the diagram are the actual pixel grey values from path number 2 in the interdental region between teeth 25 and 26 of Figure 6.1 . The horizontal line indicates the boundary between interdental space and alveolar crest. There are 14 pixels above the interdental space boundary pixel of grey value 24. The pixels change 56 levels (80-24) over a distance of 14 pixels which is a gradient of 56/14 or 4 grey levels per pixel.

A total of 5 separate bitewing radiographs were examined by the above technique and 35 interdental crest regions were investigated. The mean value and SD of the grey level gradients for all 35 crests was calculated. Those crests whose gradients fell within one SD of the mean where chosen as a subgroup of the whole sample for further analysis, to represent the average crest in a radiograph.

The subgroup crests were examined for the percentage of each crest area (%CA) found deviating from the nil change 127 value according to the grey level band spread (column 4, Table 6.3). A threshold was set of grey level deviation >= ± 2.5% of the 256 grey range (grey band numbers 3-8, column 1, Table 6.3) to separate these pixels from those which deviated by 0-2.4% of the grey range. This latter range was considered to be the minimum grey level deviation noise to be expected from the subtraction technique under ideal conditions (Bragger et al 1988b). The proportion of each crest region which contained pixels above the threshold in grey bands 3-8 was calculated for the subgroup of crests and the mean area and SD calculated for a given image displacement (Table 6.4). In this way the relationship between image displacement and subtraction image grey level deviation could be demonstrated. The threshold was then increased to a grey level deviation of >= ± 4.1% of the 256 grey range (grey band numbers 4-8, Table 6.3) to observe whether the subtraction grey deviation was primarily in the range ± 2.5-4.0% or whether a significant proportion of the crest pixels deviated by >= ± 4.1% of the grey range. The mean and SD (%CA) for the area of the crests containing pixels above the threshold deviation of >= ± 4.1% of the 256 grey range was calculated for a given image displacement (Table 6.5). It is important to know both the degree of the grey level deviation produced and area of the image affected since this indicates the sensitivity of the subtraction method for detecting small bony changes.

6.3.1 Results

The subtraction image shown in Figure 6.3 was produced by subtracting the digital copy of the image in Figure 6.1 from the initial image with **no** displacement between the images. All pixels had the nil change grey level value of 127 showing that a perfect subtraction had occured with no noise present. The potential effects from variable X-ray set output, irradiation geometry changes and subsequent film image alignment had been prevented by the experimental method. As a consequence the image had a uniform grey appearance.

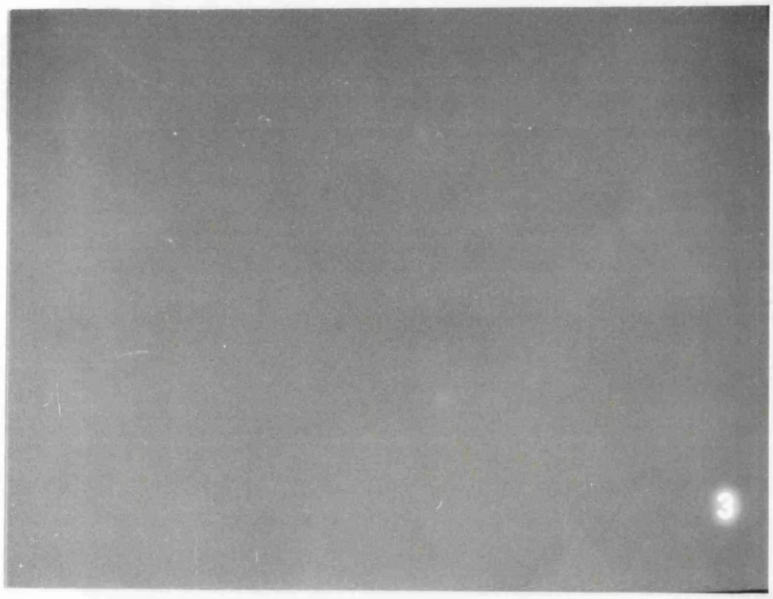


Figure 6.3 . Subtraction image formed by subtracting digital copy of image in Figure 6.1 from the initial digital image with a perfect registration between the images of zero displacement. Notice the completely uniform grey appearance and all pixels were found to have the grey value of 127.

6.3.2 Subjective assessment

The effects of selecting a horizontal displacement between the images of 0.1 mm and -0.3 mm can be seen in Figures 6.4 and 6.5. A horizontal displacement of 0.1 mm between identical images produced a subtracted image with clear anatomical outlines and alveolar bone with little detail (Figure 6.4). This would probably be reported as a good quality subtracted image from well standardized radiographs since it has a "ground glass appearance" indicating little structured noise (Revesz et al 1974; Grondahl et al 1983). It is interesting to note the distal approximal surfaces of all the teeth have light bands and the mesial surfaces dark bands in both jaws. The occlusal restorations on their most superficial aspects, where the grey gradients are highest, show alternate light and dark bands. There are no obvious light or dark bands at any of the alveolar crest margins and it is difficult to see where the interdental space ends and the crests begin.

When the images were displaced horizontally by 0.2 mm and 0.3 mm respectively, the banding was easier to see and the structured noise from the trabeculae in the alveolar bone became apparent.

When the image is horizontally displaced in the other direction by -0.3 mm all the dark bands become light and vice versa as can be seen on comparing Figures 6.4 and 6.5. This shows that the direction of the displacement, in a given plane, is unimportant in producing subtraction errors and that the only difference will be whether a false density gain or loss is shown.

Figure 6.4. Subtraction image formed by subtracting identical images with a horizontal displacement of X= 2 Y= 0 pixels (0.1 mm). Pixel= 0.05 x 0.05 mm. Notice alternate light and dark grey bands on approximal surfaces of teeth.

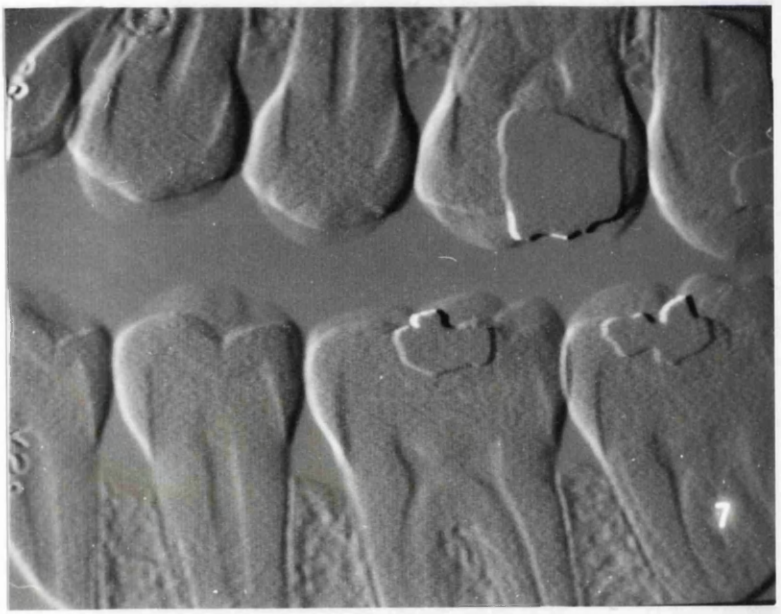


Figure 6.5 . Subtraction image formed by subtracting identical images with a horizontal displacement of X= -6 Y= 0 pixels (-0.3 mm). Notice alternate light and dark grey bands on approximal surfaces of teeth have reversed compared to Figure 6.4 . The intensity of the bands is greater due to the larger displacement.

Subtraction images produced by vertical displacements of 0.1 mm and -0.3 mm can be seen in Figures 6.6 and 6.7. A small vertical displacement of 0.1 mm between subtracted images produces an image where large areas have a ground glass appearance as in Figure 6.4 but again there are false light and dark subtraction bands. However, there are important subtle differences with all the approximal tooth surfaces in the maxilla having dark bands and all the mandibular surfaces having light bands (Figure 6.6). These bands are smaller in size and more difficult to see. All the occlusal surfaces of the maxillary teeth have light bands while the mandibular ones have dark bands. Unlike the subtracted image from the horizontal displacement, the alveolar crest margins can be seen with light outlines in the 25-26, 26-27 regions and dark outlines in the 34-35, 35-36 and 36-37. These regions were easier to see as the vertical displacements increased to 0.2 mm and 0.3 mm. When the direction of the displacement is reversed -0.3 mm all the light and dark regions changed as before (Figure 6.7).

Interestingly, the oblique displacements between the images cause grey light and dark bands which produce errors characteristic of horizontal and vertical displacements. These show alternate light and dark approximal surfaces together with light crests in the maxilla and dark ones in the mandible.

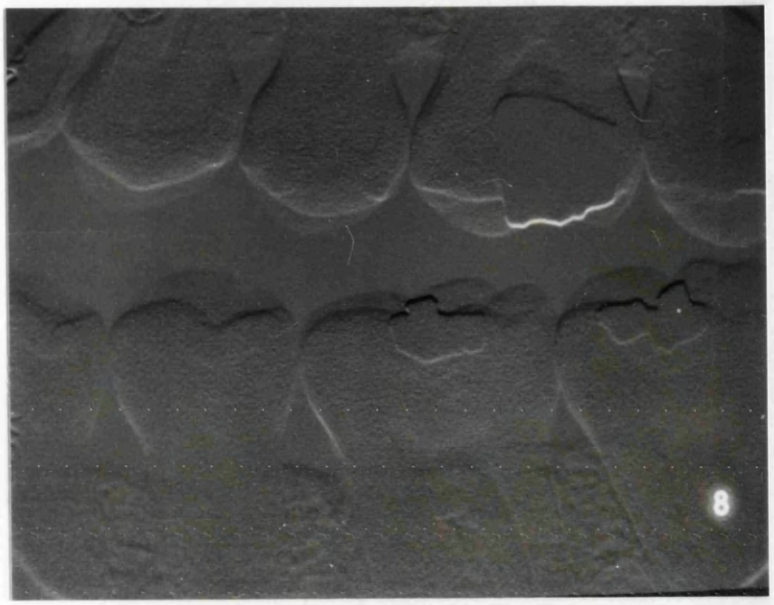


Figure 6.6 . Subtraction image formed by subtracting identical images with a **vertical** displacement of X= 0 Y= 2 pixels (0.1 mm). Notice light grey bands on maxillary occlusal surfaces and crest 26-27. Dark grey bands are seen on mandibular occlusal surfaces and crest 35-36.

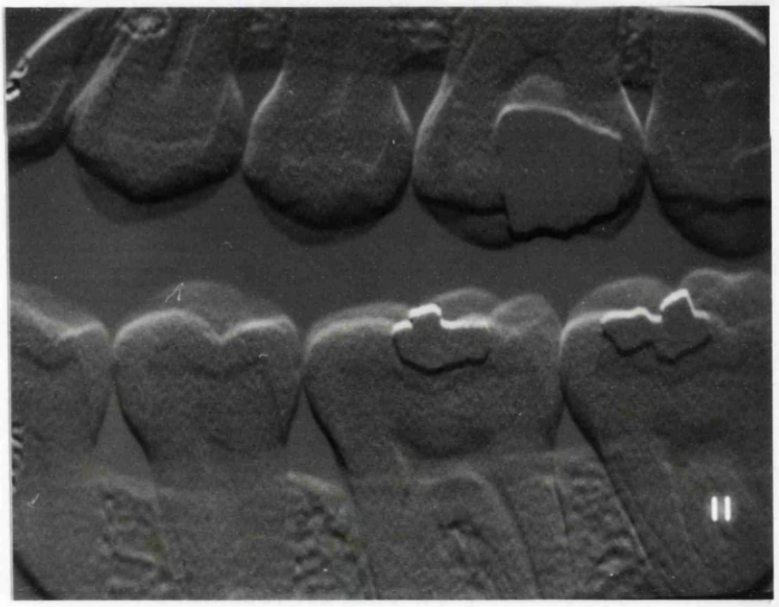


Figure 6.7 . Subtraction image formed by subtracting identical images with a **vertical** displacement of X= 0 Y=-6 pixels (-0.3 mm). Notice dark grey bands on maxillary occlusal surfaces and crests 25-26, 26-27. Light grey bands are seen on mandibular occlusal surfaces and crest 34-35, 35-36. The light and dark bands have reversed with change of displacement direction compared to Figure 6.7 .

6.3.3 Objective assessment

The grey level gradients across the 35 alveolar crest margins from the 5 bitewing radiographs were found to have a mean of 3.1 (SD) 1.4 grey levels per pixel. Twenty-one crests (58% of the total) with a gradient within the range of 3.0 $\pm$ 1.0 grey levels per pixel were selected as a subgroup to represent the average image crest. A threshold was applied to each subgroup crest region of >= $\pm$ 2.5 % deviation of the grey range about the nil change 127 level. The percentage of the crest area above the threshold for all the crests, with a range of image displacements, was found to be 9.0% (SD) 4.5 %CA (displacement X direction 0.1 mm) to 62.2% (SD) 16.6 %CA (displacement XY= 0.42 mm) (Table 6.4). With a higher deviation threshold of >= 4.1% of the grey range the values were 1.9% (SD) 1.9 %CA (displacement X= 0.1 mm) to 45.9% (SD) 20.8 %CA (displacement XY= 0.42 mm) (Table 6.5).

For a comparison with the alveolar crests, the grey level gradients at a tangent to the mesial approximal surfaces of teeth 26 and 36 were measured using the same method. The gradients were 20.5 and 14.9 grey levels per pixel respectively.

Three alveolar crest sites were chosen from the image in Figure 6.1 to represent the range of gradients found in the images. These were between the teeth 36-37, 25-26 and 26-27 with the gradients of 2.3, 4.1 and 6.3 grey levels per pixel respectively. A subtraction image was formed by using images with a vertical displacement of 0.1 mm between them (Figure 6.6). The %CA which fell into the high grey

deviation band of 4.1-7.9% for each crest was 1.1%, 12.3% and 19.5% in order of ascending crest gradients.

The grey level gradient in the vertical direction across the crest region between the teeth 26 and 27 (Figure 6.1) was found to be 6.3 grey levels per unit pixel distance of 0.05 mm. This is an example of a high gradient crest.

The distribution of the subtracted grey levels from the crest region between the teeth 26, 27 can be seen in Figure 6.8, displayed as the proportion of the crest area examined with a given grey level deviation from the nil change 127 value. Less than 1% of the crest pixels were in the high grey deviation range of 8-23% of the grey range. This is for the horizontal displacements of 0.1 mm, 0.2 mm, 0.3 mm and -0.3 mm.

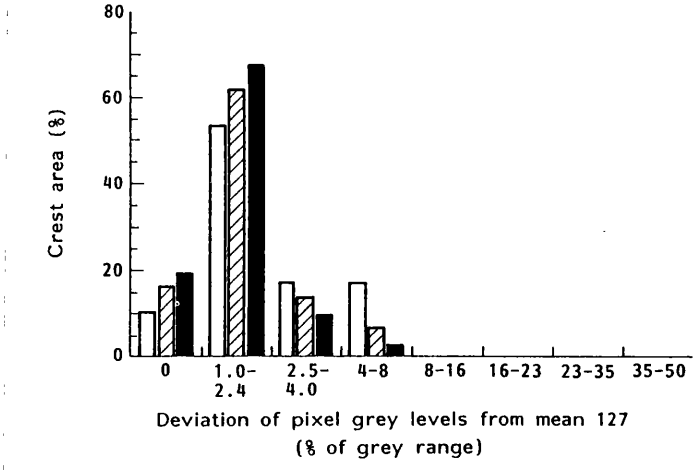


Figure 6.8 Grey level deviations due to horizontal image displacement. Data from subtraction images of crest region 26-27 of Figure 6.1 with crest gradient of 6.3 grey levels/0.05mm pixel. Deviation of subtraction grey levels proportional to displacement between images. Image displacement X direction ■=0.1mm, ▨=0.2mm, □=0.3mm; Y=0mm.

A vertical displacement has a far larger effect on the magnitude of the false bone loss and gain than a similar horizontal displacement. Thirty-seven percent of the crest pixels were in the high grey deviation range of 8-23% of the grey range for a displacement of 0.3 mm. The grey level deviation from 127 for the whole range of vertical displacements is shown in Figure 6.9.

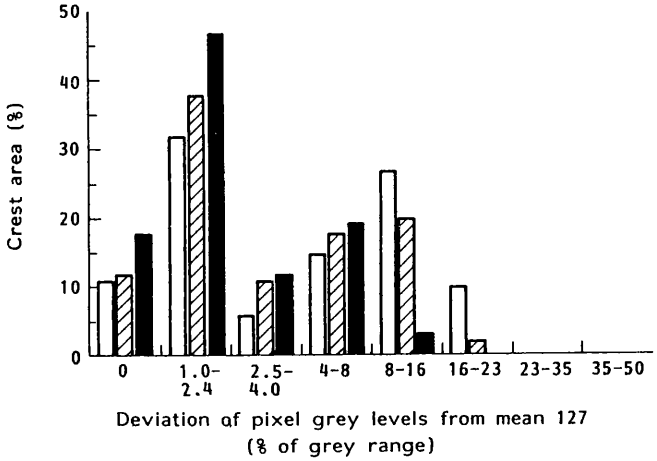


Figure 6.9 . Grey level deviations due to vertical image displacement. Pixel grey level distribution from subtraction images of crest region 26-27 of Figure 6.1 . A vertical image displacement produces a greater subtraction grey level deviation than the equivalent horizontal displacement in Figure 6.8. Image displacement Y direction ■ =0.1mm, ▨ =0.2mm, □ =0.3mm; X=0mm.

An oblique displacement between the images of 0.14 mm, 0.28 mm, 0.42 mm and -0.42 mm before subtraction caused 34% of the crest pixels to be in the high grey deviation range of 8-23% of the grey range for the largest displacement.

Surprisingly there is very little difference between the grey level distributions in subtracted images from vertical displacements alone or oblique displacements (Tables 6.4, 6.5).

6.4 Discussion

The smallest displacement of 0.1 mm was chosen for these experiments using the assumption of a pixel size of 0.05 mm by 0.05 mm being used in clinical practice. This is equivalent to a number 2 sized film filling a monitor screen. Since image registration is a pixel-based activity, it seemed reasonable to use a multiple of the pixel size to investigate misregistration errors. Even though mechanical registration to an accuracy of one pixel or 0.05 mm is feasible, radiographic images are unsharp and an alignment error of 0.1 mm was chosen as the anticipated discrepancy in subjective positioning of a film for subtraction.

From the results it would seem that one can deduce by the pattern of light and dark bands on the approximal and occlusal surfaces whether a displacement between images has occured and more importantly whether it has a vertical or oblique direction. This should alert the clinician to the possibility that the dark or light patches they are seeing are in fact false ones due to method errors.

The data in Tables 6.4 and 6.5 indicate that a small displacement of 0.1-0.3 mm between images can cause 20-60% of the pixels, in an

alveolar crest margin, to deviate by at least ± 2.5% of the grey range from the nil change 127 grey value. This seems to indicate a serious risk of producing false bone changes in the subtraction technique by small image displacements. The higher deviation threshold of at least ± 4.1% of the grey range revealed that a large proportion of the deviated pixels had grey values at least ± 11 and possibly as high as ± 20 grey levels from the 127 nil change value, increasing the chance of masking true bone change.

It would therefore seem sensible to raise the threshold deviation value to at least ± 8% of the grey range (± 21 grey levels) from the nil change 127 value. This is considerably higher than the ± 2.5% of the grey range (± 6.6 grey levels) recommended by Bragger et al (1988b). As an approximate quantitative guide, ± 8% of a dense alveolar crest margin 10 mm wide in the bucco-lingual direction which produces a 'white' line in a radiograph, would be approximately equivalent to ± 0.8 mm of cortical plate. This might indicate that lesions equivalent to this mass might be undetectable due to image registration errors. Although Grondahl et al (1988) reported the ability of detecting artificial lesions, 0.5 mm deep into dry mandibular buccal cortical bone, this was without any simulated cheek scattering of the X-ray beam which would have increased the image noise.

The range of grey gradients for all 35 crests was 0.8 to 6.2 grey levels per pixel whereas the subgroup of 21 crests ranged from 2.0 to 4.0 grey levels per pixel. Although the use of a high threshold for

pixel grey level deviation from the nil change 127 level (>= ± 8.0% of the grey range or ± 21 grey levels) can be justified from the above discussion, it is a coarse method since in any one radiograph, individual crests may have a gradient varying from 0.8 to 6.2 grey levels/pixel. A small displacement between images of only 0.1 mm will produce from a crest gradient of 0.8 a grey level deviation from the mean of ± 1.6 grey levels per 0.1 mm (gradient x displacement distance). A larger oblique displacement of 0.42 mm will result in a grey level deviation of ± 6.7 grey levels which is one third of the threshold. However, a crest with a gradient of 6.2 will produce deviations of ± 12.4 and ± 52.1 grey levels for image displacement between images of 0.1 mm and 0.42 mm respectively. Clearly in this situation the threshold deviation should be larger than ± 21 grey levels for displacements greater than 0.1 mm.

An alternative solution would be to select a threshold for each site based upon the gradient found across the crest margin in the initial grey image. If a registration error between images of 0.1 mm is always assumed then the grey deviation error will be the gradient per 0.1 mm. This could be doubled to allow a margin of safety in setting the threshold deviation. In this way a crest with a gradient of 0.8 would be thresholded at ± 3.2 grey levels and a crest with a high gradient of 6.2 thresholded at ± 24.8 grey levels. This would allow a grey level deviation threshold to be selected for each crest site in a subtracted image which should be appropriate to masking subtraction errors without hiding true bone changes.

The above observations and suggestions will aid researchers in interpreting and extracting data from subtraction images. However, although such changes may improve the usefulness of the subtraction technique, the method is fundamentally flawed. The development of individual crestal grey deviation thresholds is necessary due to errors inherent in the subtraction technique and not due to limitations of radiography, film technology or digital image processing. The primary problem of the subtraction technique is its lack of any computational representation for anatomical structures. If a suitable set of grey level image features were selected to represent cemento-enamel junctions (CEJ), alveolar crest margins, trabeculae, then distances and density changes would be measured within images and the distances compared between images rather than blindly subtracting one image from another. There would still be reliability errors of $<= \pm 0.15$ mm in measuring CEJ-crest distances due to unsharpness of radiographic images, leading to variability in picking the position of the reference points (Chapter 5). However, this small linear error is confined to measurements made within each film and is independent of the film position under a video camera. It is very important to appreciate that these subtraction errors produced by displacements between images are unique to the subtraction method. These particular errors do not occur if a non-subtraction method is used, based upon measurements made between reference points in one image and compared with measurements made in another image.

The subtraction method can, under very rigorous clinical and laboratory conditions, enhance images for subjective detection of bone

loss although there is a high risk of methodological errors as described in this work and elsewhere (Ruttiman et al 1981; Grondahl et al 1984; McHenry et al 1987).

If the subtraction method is used, it would be useful if researchers reported their image displacement errors using a slightly modified version of the method in this work. Instead of producing two identical digital images from one radiograph, a radiograph should be digitized representing an initial film and then removed from the film carrier. The carrier should be moved into a slightly different position before the same film is replaced, the film carrier realigned with the original image under the camera as normal and digitized to represent a subsequent film. In this way the ability of the operator/system for registering films for subtraction is tested and the separate compounding errors of changes due to exposure, irradiation geometry and film processing changes avoided. The grey level gradients across the alveolar crest regions can be measured and the pixel grey level deviation from the nil change 127 level measured for the crest margins as described in the current work. In this way an objective estimate for the displacement errors produced by each laboratory can be made. Currently there is no generally accepted method for objectively reporting subtraction errors.

A significant benefit to be gained by abandoning the subtraction technique is that it would become unnecessary to use occlusal moulds or cephalostats for rigidly controlling the irradiation geometry. Beam-aiming devices would still be needed to prevent angular

variations of greater than 3^{o}. However, sufficient standardization can probably be achieved by a new design of a stentless repositionable holder, as described by this author (Appendix V).

Researchers should not forget that although the subtraction method produces light and dark patches which are easy to see, these patches can easily be formed by errors of the technique and they are indistinguishable from true disease changes. This work has demonstrated how very acceptable subtraction images can be formed which are due only to methodolgical errors. False bone gain and loss are apparent in alveolar crest margins which are particularly susceptible to vertical or oblique misregistration errors. With so many deficiencies of the subtraction method it is very difficult to justify its continued use in dental research. It is time to look at new methods which have a sound theoretical computational basis and will be practical for general dentists to use.

6.5 Conclusions

A computer-based investigation has revealed a new major methodological error in the digital subtraction method. When added to the list of known technical limitations, the digital subtraction method is unlikely to provide an accurate estimate of early dental disease.

Chapter 7 The development of a computer-based method to assess the feasibility of automating image analysis of bitewing radiographs.

7.1 Introduction

Making accurate measurements from enlarged images of intra-oral radiographs is a time consuming activity. Selikowitz et al (1981) took 30 minutes to measure alveolar crest margin levels from a bitewing radiograph using a microfiche enlarger and calipers. Al-Kufaishi (1982) using a similar method needed 10-12 minutes for a set of 4 readings from 2 molars. Pitts (1984) using an objective computer-based method for measuring caries, required approximately 60 minutes of operator time to select all the approximal regions in a radiograph. Verrier et al (1989) needed 15 minutes to compare the density of one interdental bone region between 2 serial films. The computer-assisted measuring method, described in Chapter 5, needed the least operator time of about 7 minutes for making 14 duplicate cement-enamel junction (CEJ) to alveolar crest measurements. Additonal time is also required with manual methods for calculating the changes between serial films.

Diagnostic and monitoring methods which require long periods of skilled operator interaction are unlikely to be acceptable for routine use in general practice, or even for extensive research studies. Ideally the measuring process should be simple and fast enough for dental nurses to perform reducing operating costs. A high degree of automation is required to achieve these aims.

Automatic image analysis requires the computer to create a model of the anatomical structures and their spatial relationships in an image (Marr 1982). Research in artificial intelligence (AI) has shown that unless models can be constructed, there is very little hope of completely automatic image analysis (Ambler and Barrow 1975, Levine 1978, Marr and Nishihara 1978. Perkins (1978) demonstrated that assembly of a limited number of mechanical parts with known shapes required a complicated model using 2D geometric image features of outline curves, holes and areas. Analysis of complex radiographic images is an even harder task since considerable structural variation can occur from film to film.

Model-based image analysis is thought to be equivalent to human "seeing" since until you know what is in an image you cannot recognise it. Seeing has been likened to controlled hallucination where the brain attempts to match image features against stored models of objects (Bowden 1979). The use of knowledge is important to image recognition since it is an active process (Marr 1982). Human observers can recognise a chair despite the fact most of it is hidden by a person seated on it (Bowden 1979). The active use of stored knowledge, such as models of chairs representing 3D structure and function of chairs, is the supposed mechanism for recognising partially hidden objects (Ambler and Barrow 1975, Levine 1978, Marr and Nishihara 1978, Perkins 1978).

Although the use of contextual knowledge is important, how things are

spatially structured and used, it is believed to be applied late in the recognition process following the production of image features (Marr 1982). Image features or primitives describe points of interest such as regions of steep grey level gradients or edges between areas in an image. These meaningless features can be grouped together by pattern recognition techniques to reveal potential structures which may be parts of objects, such as cusps of teeth, pulp horns or alveolar crest margins. In addition the grouping process can aid the rejection of features formed from image noise.

Knowledge can be used to decide whether the potential structures are good candidates for matching against stored models or should be rejected early in the recognition process. Image features identified with a high degree of certainty, such as interdental bone crests, can be utilised to help classify other features since there is a large a amount of ambiguity in recognising image structures. The process of sequential classification of image features depending upon a high level of confidence being achieved, is a very important principle to grasp (Marr 1982).

In dentistry, the automatic recognition and identification of skeletal landmarks from lateral skull radiographs has been investigated by Cohen et al (1984). Although a computer was able to identify menton and sella, it nevertheless required initial delineation of the regions of interest by a human operator. Similarly the objective radiographic method devised by Pitts (1984a) for measuring approximal carious lesions needed initial human guidance.

Recently Davis and Taylor (1989, 1990) reported a completely automatic method for analysing lateral skull cephalometric radiographs using an image model approach. The method used a blackboard architecture containing different levels of information ranging from pixel grey levels at the bottom extending to a list of potential anatomical structures at the top. At any one time a number of program modules can be writing their findings into the blackboard while others inspect its contents to see if it is consistent with a hypothesis for adding a potential image feature. The continual hypothesis, test and modify cycle of the blackboard architecture makes it a powerful AI analytical method but it is a complex structure to create in software and difficult to control its operation.

Davis and Taylor (1990) reported that on 20 test images, the method was 80% successful in finding features such as sella, pogonion and nasion. The system required several hours to process one image but nevertheless this is an example of a completely automatic image anlysis method.

A search of the medical literature has shown that no general purpose automatic imaging system exists but a small number of automated methods (requiring some human interaction) can be found.

Chan et al (1987) developed an automated method for detecting microcalcifications in mammography. A form of digital subtraction radiography was used to enhance an image and potential tumours identified by statistical techniques providing 80% true positives and

1 false positive per image.

Giger et al (1988, 1990) developed an automated lung nodule detection system for analysing chest radiographs. Unfortunately there were about 4 false positive nodules per image in the medial and lateral lung margins and this may have been due to the lack of an image model.

Nakamori et al (1990) developed an automated model-based method for estimating the sizes of heart and lungs in chest images but it performed accurately only with sharply defined organ shadows.

No completely automatic image analysis method for bitewing radiographs has been reported where no initial human guidance was performed.

The aim of the present work was to develop software for a pilot study, to assess the feasibility of automating the identification of approximal tooth regions and interdental alveolar crest margins from bitewing radiographs. This is the important first stage required before automatic objective measurements and comparisons can be made between serial films. In AI terms, this chapter reports on a knowledge-based pattern recognition method for producing a hierarchical model to classify structures in a radiographic image.

7.2 Materials and Method

7.2.1 Key image features

A preliminary visual inspection of 10 bitewing radiographs was made, to look for features which could help in the recognition process. In all the radiographs the darkest portions were the interdental space regions and the area between the occlusal surfaces of the upper and lower teeth.

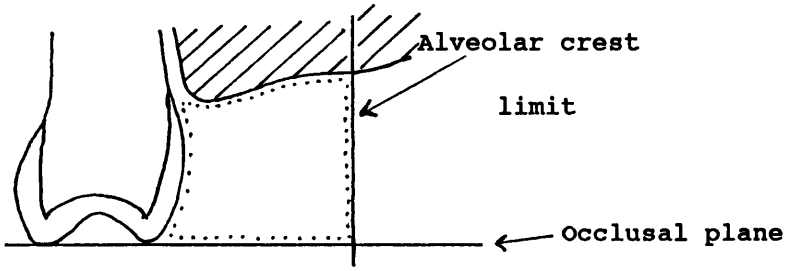
It was decided to develop a method which depended on the identification of interdental spaces for the following reasons :-

1) The interdental spaces are bounded by the approximal tooth surfaces and alveolar bone crest margins which are potential sites for disease. If adjacent teeth are in contact, a closed interdental space is formed with the potential caries zone stretching from the CEJ area to the radiographic contact point (Figure 7.1a). Even when adjacent teeth are not in contact, a bounded region can be formed by the alveolar crest margin, an approximal tooth surface, the occlusal plane and an approximal surface from a different tooth (Figure 7.1b). Distal extension saddles, where a tooth is the most posterior in a partially edentulous arch, can still fit into the scheme since an alveolar crest margin, an approximal tooth surface and an occlusal plane are present. By limiting the distal extent of the alveolar crest and the occlusal plane, a bounded region can be formed (Figure 7.1c).

2) The distance between interdental spaces can be used to determine the size and type of teeth present in a radiograph. The width of a tooth can be defined as the distance between the most distal point of the interdental space, on its mesial surface, and the most mesial point of the space on its distal surface.

a) Closed

b) Open



c) Partially edentulous

Interdental space boundary .....

Figure 7.1 Classification of interdental space types

In Figure 7.2 all the interdental spaces are "closed" due to contact with adjacent teeth. The large interdental space between the mandibular molar and premolar can also be classified as closed, since the bridge pontic separates this region from the "open" interocclusal area.

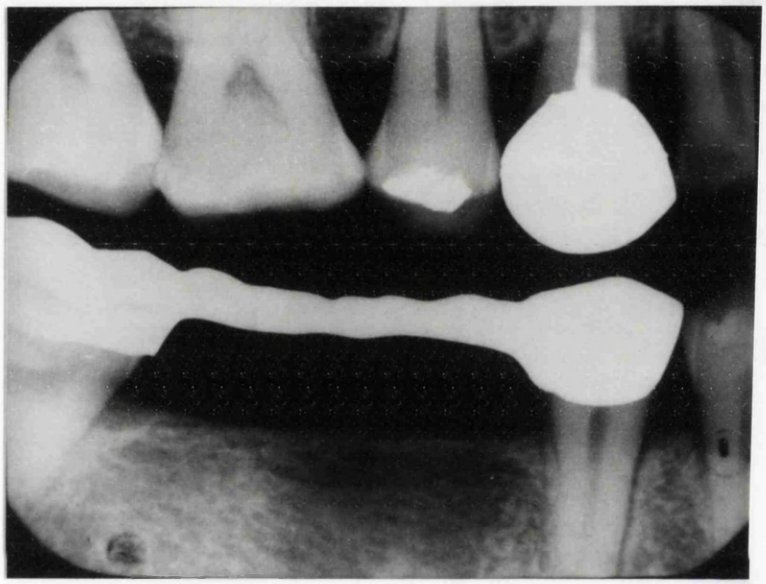


Figure 7.2 Right bitewing digital image viewed from monitor. Magnification x6.

The width of the premolar tooth 15 (FDI notation) can be compared to the size of molar 16 using the proposed interdental space method. The premolar is two thirds the width of the molar and this is a strong clue to its type.

3) The mesio-distal extent of closed interdental spaces is a reliable guide to the presence of bridges. In Figure 7.2 the interdental space between the mandibular molar and premolar is greater than one molar width and is highly indicative of a bridge pontic.

By applying these principles to Figure 7.2, the radiograph could be

analysed to contain 3 maxillary teeth, a mandibular bridge and a mandibular molar. However, the teeth 17, 13, 47 and 43 would not be identified since the limited size of the radiograph prevents the interdental spaces from being seen on both sides of these teeth. The approach therefore needs a modification to be able to cope with teeth which have incomplete images in order to classify them. The additional information required can be supplied from the teeth already classified as molars, premolars or canines in the image using a set of rules as follows:-

If 3 teeth can be classified as maxillary molar, premolar and premolar (teeth 16, 15 and 14 in Figure 7.2) then the unknown tooth distal to the molar has a high probability of being a molar. Similarly if a tooth mesial to 2 maxillary premolars is found, it has a high probability of being a canine.

Following on from this, if a mandibular premolar (tooth 44 in Figure 7.2) has been classified, then the tooth mesial to this is a canine. In a like manner, if a space large enough for 2 molars is found distal to the tooth 44 and an abutment tooth is found, it has a high probability of being a molar.

The proposed method can be described as a sequential process of i) initial detection of interdental spaces and classification of tooth type from width and position, ii) the subsequent use of this information in conjunction with additional knowledge or rules, to classify unknown tooth or crest regions. This approach to automatic

image analysis closely conforms to the general AI principles described by Marr (1982).

7.2.2.1 Image model design

The preceeding section describes the idea of finding interdental spaces and applying knowledge in the form of rules as a proposed method for analysing images. However, it does not provide a strategy for processing grey level pixels to reveal where the interdental spaces are to be found in an image. Neither does it suggest a data structure which is capable of allowing comparisons between regions in serial films.

A model can be thought of as a representation of something. To analyse images it is essential to have a model which would allow a machine to compare images in a clinical way. A good test would be for it to identify a particular tooth surface in radiograph 1, find an approximal radiolucency and characterise it by greyness and spatial extent. The same procedure would then be performed in a subsequent image from serial film 2 and the findings compared for change or caries activity. Although caries has been given as an example, it should of course apply equally well to alveolar bone crests.

However, this deceptively simple task for a human requires several different levels of anatomical description. The highest level should store tooth types so that a specific tooth such as "maxillary first molar" can be defined in an image. The next level down should contain

parts of that tooth such as "approximal surface" or "occlusal surface". Beneath this should be subdivisions of the previous region such as "between the CEJ and the contact point". Each of these English-like or semantic descriptions would be accompanied by spatial information which would describe where it could be found in the image which has been used to create the model (Figure 7.3).

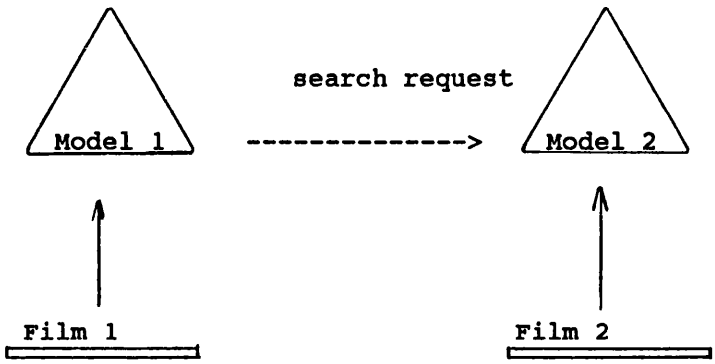


Figure 7.3 Inter-model communication for searching and comparing radiographic areas of possible disease.

7.2.2.2 Image model levels

The proposed computer model of a bitewing image has a multi-layered structure as shown in Figure 7.4. It is in essence a pyramidal structure with the lowest level of pixel data at the base. As one proceeds through to higher levels, the information stored becomes less like the original grey levels and more abstract until at the apex an English-like description is produced. In passing from the lowest model

level, where a 440 kilobyte (K) image is stored, to the highest requiring only about 4K, a large data reduction of 100:1 occurs which is very economical in terms of data storage. The contents of each level are as follows.

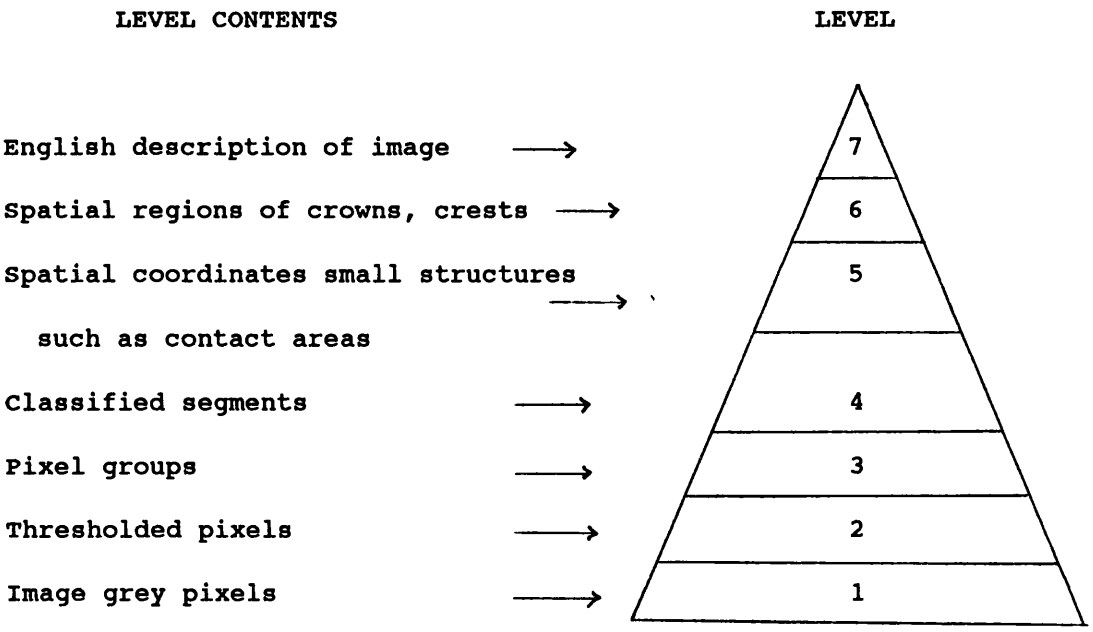


Figure 7.4 Multiple layer structure of image model.

Level 1

This is the base of the model and contains 768 by 575 grey level numbers representing the grey level value of each image pixel. No processing has been performed on this image since it is a direct copy of the contents of the frame store.

Level 2

The next higher level contains the X, Y coordinates of thresholded

pixels which represent positions of high grey level gradients or edges. Some of these will be at the occlusal or approximal surfaces of teeth and others at interdental alveolar crest margins.

Level 3

This level contains pixels, from the level below, which have been grouped together because they are spatially close together. The idea being that pixels which are near to each other are likely to share common properties, such as belonging to the same tooth surface or crest margin.

Level 4

Here the pixel groups from level 3 are arranged into segments or short chains which are classified into anatomical structures, such as tooth surfaces or bone crests.

Level 5

At this level the information ceases to be concerned with individual or groups of pixels. Instead it stores the spatial coordinates of anatomical structures, for example the anterior end of an alveolar crest margin.

Level 6

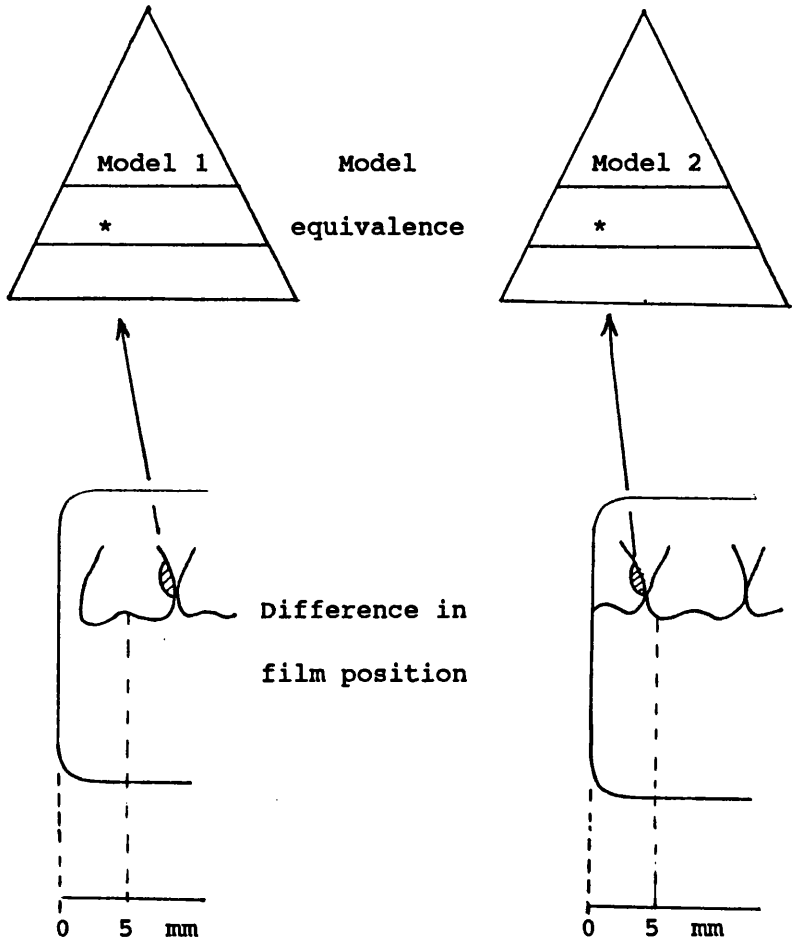
The scale of the structures represented, at this level, increases to regions containing crowns of teeth and interdental spaces.

Level 7

Here is the apex of the model with an English-like (semantic) description of teeth, interdental spaces and their associated types such as molars and premolars. The order of the anatomical structures in this layer corresponds to their left to right position in the original image.

The importance of semantic descriptions is that they can provide a way for a computer to identify the same anatomical region in different images without requiring absolute spatial coordinates. This produces a spatial independence between films so that small variations in positioning a film in the X, Y planes of the mouth will not affect comparisons between films. Providing the computer can create in model 1 from film 1 the "maxillary third molar mesial approximal surface" and form the same in model 2 from film 2, it is of no consequence at all if these regions are in slightly different positions in the 2 films (Figure 7.5). However, for techniques such as subtraction radiography any spatial misregistration between serial films produces artificial changes (see 4.6.4.2 and Chapter 6).

In the current model, no layers specifically exist for densitometric and spatial characterisation of disease, although these can be added as new layers or extensions to existing layers.



* Mesial approximal surface model representations are equivalent despite differences in absolute spatial position between radiographs.

Figure 7.5 Image model independence of variable film positioning.

7.2.3 Metaknowledge

Metaknowledge is information which describes what is known about a situation or can be knowledge about knowledge (Barr and Feigenbaum 1981). Metaknowledge can be information generated by a computer program about its own progress. In the current work, metaknowledge has been created by the program to provide information on features found in the images to aid the computer processing. The maxillary and mandibular occlusal planes are calculated in each image by the program which assists in determining which structures relate to which jaws. The occlusal planes are virtual structures, since they are conceptual with no physical reality. Metaknowledge is also created concerning the numbers and types of interdental spaces found in an image, in case a space has not been detected. If the program suspects it has missed a space, it calculates the likely area and searches for it.

In general terms, the more metaknowledge a program can generate, the greater the chance for classifying unknown image structures.

7.2.4 Confidence

Metaknowledge provides information to allow an educated guess to be made about a possible image structure and this will have an associated degree of uncertainty. The program, in addition to hypothesising that structures such as interdental spaces are present, also links a confidence value to them ranging from 0-100%. This

provides a way for using structures, which have been classified with high confidence values, to aid in classifying unknown structures.

7.2.5 Knowledge-based rules

It has been stated that incorporating knowledge into models or programs is important for recognising image structures (section 7.1). In this work, knowledge has been incorporated in the form of production rules of the "IF ..... THEN ....." format (Winston 1977). An example being "IF the approximal surface found is above the maxillary occlusal plane THEN it must be from a maxillary tooth." In practice rules are more complicated of the form "IF ..... and IF ..... and IF ..... THEN ..... is true."

The importance of metaknowledge, confidence values and production rule knowledge can be seen in several practical applications in this work. One example is the problem of finding interdental spaces.

It is common that a small interdental space which looks black may have a value as high as 64 grey levels, from a range of 0-255 (see interdental space between teeth 17,16 in Figure 7.2). Often the space will not initially be detected by the program. However, providing the next space is found with a confidence value of at least 90%, the computer will calculate the likely region for a missing interdental area and return to search for it. A program which does not expect incomplete initial classification and does not have the mechanisms to cope with this situation, will not be able to achieve automatic image

classification.

7.2.6 Program design

The program was written by the author in the "C" application language. The development and testing required one man/year of work, produced 6,000 lines of source code and used 50 production rules. In use the program requires 2 minutes of computer operating time to process one image to the stage of finding the interdental spaces and creating the image model.

The design and operation of the program will be discussed in relation to the data model structure (Figure 7.4).

Level 1 contains a 768 by 575 array containing a grey image digitised to 7 bits (128 grey level resolution covering the range 0-255 grey levels in steps of 2 levels). Level 1 has therefore the unprocessed input image as in Figure 7.2.

Level 2 contains a tertiary image of only 3 grey values (black, midgrey and white pixels) which is produced from the image in level 1. The reduction from a full range of grey levels to only 3 is achieved by applying a threshold vertically to each column of pixels in the image.

The first pixel which is found below the threshold is marked with a white grey value (the broad intense white lines seen in Figure 7.6)

and corresponds often to either a maxillary interdental alveolar crest or an occlusal surface. The search proceeds further down the column until the threshold is exceeded either by a maxillary approximal surface (coronal to the alveolar crest margin) or a mandibular occlusal surface (inferior to a maxillary occlusal surface). These pixels are marked by a midgrey value and appear as the thinner less intense lines in Figure 7.6.

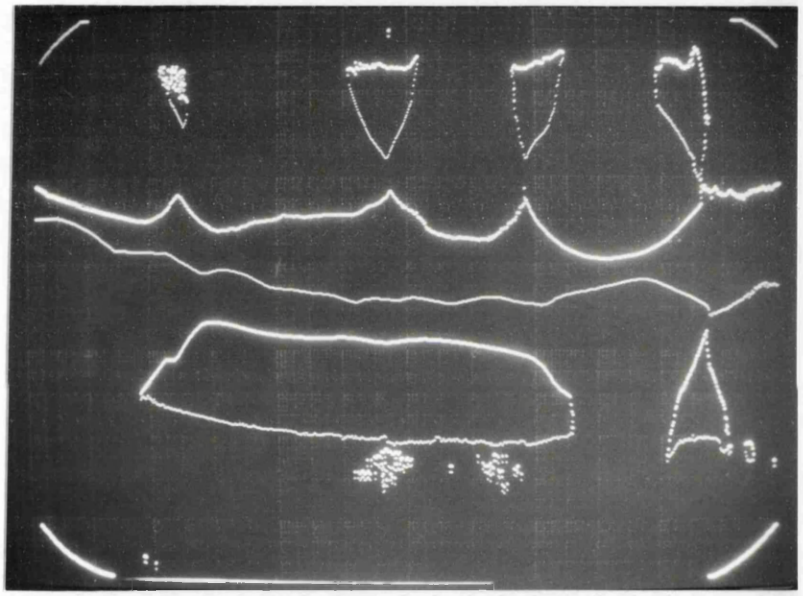


Figure 7.6 Monitor image of thresholded pixels in Level 2 of model.

The examination of the pixel values in the vertical column continues until either a mandibular interdental alveolar crest or an occlusal surface is found by the threshold being exceeded. The pixels are again marked by a midgrey level. When the lower border of the image is reached, the search recommences at the top of the next pixel column to the right and this is repeated until the whole image has been covered.

The vast majority of the pixels are not at the borders of the tooth

surfaces or the crest margins and so have a black grey value. It should be emphasised that the different grey level markings are not for human viewing as the whole process is automatic. However, in the development, testing and explanation of the program's actions it is extremely useful to be able to see the processing activity.

In computing terms, the image operation just described is a grey level threshold operator, capable of detecting increasing or decreasing grey gradients in the vertical direction.

The grey threshold for determining the boundary between 2 regions is created by examining every tenth pixel, which is more efficient than every pixel, in the array of level 1. For every pixel examined, the grey level value found increases the pixel total count by one for that particular grey level. If the total number of pixels for each grey level is plotted as a graph, a bi-modal curve is produced. The dark grey level peak in the graph is produced by pixels found in the interdental and interocclusal space regions of the image. The light grey level peak is formed from pixels originating from pixels in the tooth and bony regions of the image. The valley between the peaks is composed of the few pixels found bordering the coronal surfaces of the teeth and the alveolar crest margins with the darker space regions.

By trial and error, it was found that by selecting a threshold value just above the bottom of the grey level valley, the best results were produced with minimum noise. An example of noise can be seen in the bone below the alveolar crest margin midway between the mandibular

molar and premolar, as 2 groups of about 100 pixels in Figure 7.6.

Despite several attempts at varying the sampling method, it was found that no single threshold could be produced which would allow correct partitioning of the image into tooth, bone and space regions. This was due to the fact that even though the eye identified space regions as being black, in objective terms the actual dark regions could have values up to one quarter of the full grey range. The eye compares regions and the brain experiences the differences as areas of relative greyness. In Figure 7.2, the interdental space regions although looking the same to the eye, will have values of 18 grey levels between teeth 14,13 and 52 grey levels between 17,16 (see far right column of Figure 7.11). A single threshold which is set at 18 grey levels would be ideal for 15, 14 and 14,13 interspace regions but too low to detect region 17,16. Similarly a threshold set at 52 grey levels would detect region 17,16 but would produce a lot of confusing noise from the bony trabeculae.

In general the threshold is automatically set so that the majority of the interdental spaces, with low grey level values, are thresholded producing many crestal pixels, while the high grey level spaces produce fewer.

The variations, in the interdental space grey levels, were not due to gradation from the back illumination of the film, since this was measured by the computer and found to vary by only 5% of the grey range across the whole field. The variation of the interdental space

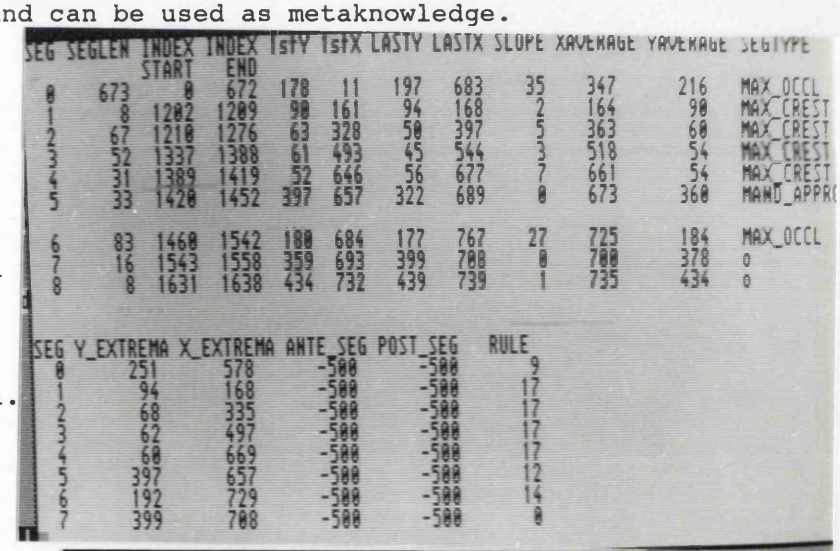
grey values were likely to be due to different thicknesses of cheek and interdental papillae in the X-ray beam direction.

Although this single thresholding method produced noise and occasionally failed to find interdental space pixels, it did provide a source of pixels which were potentially from the boundaries of teeth and bone. However, there was no difference between noise pixels and pixels from anatomical structures.

Level 3 has the task of collecting together individual pixels from level 2 and identifying those which are spatially close together. The program examined each thresholded pixel in level 2 to see if it had a neighbour within a certain distance, set previously by trial and error. In this way pixels, which might belong to the same portion of tooth or bone, were grouped together. Although this might seem unimportant, the process of assigning a property to a collection of pixels is a form of classification, which differentiates them from other pixels and leads ultimately to them having a special meaning. However, at this level all pixel groups, although separate spatial entities, have no special meaning since there is no difference between noise groups and anatomical boundary groups.

Level 4 has the function of examining the pixel groups from level 3 for special properties, which together with production rules (section 7.2.5) can be used to anatomically classify the pixel groups into segments.

The properties tested for in each group were the length in pixels, the X and Y coordinates of the first and last pixel, the slope of the group (which tended to be linear), the average X and Y values and the extreme X and Y values. If these properties fell into a pattern which could be matched with a production rule (equivalent to pattern recognition), an anatomical classification was made. In Figure 7.7 nine segments are listed from 0-8 with their properties and at the right edge of the table, the segment classification type is given. Segments 0-6 have been correctly classified and segments 7-8 remained unclassified since no pattern recognition could be made. In the lower smaller table of Figure 7.7 the rule which classified the segment is also available and can be used as metaknowledge.



SEG	SEGLEN	INDEX START	INDEX END	FstY	FstX	LASTY	LASTX	SLOPE	XAVERAGE	YAVERAGE	SEGTYPE
0	673	0	672	178	11	197	683	35	347	216	MAX_OCCL
1	8	1202	1209	90	161	94	168	2	164	90	MAX_CREST
2	67	1210	1276	63	328	50	397	5	363	60	MAX_CREST
3	52	1337	1388	61	493	45	544	3	518	54	MAX_CREST
4	31	1389	1419	52	646	56	677	7	661	54	MAX_CREST
5	33	1420	1452	397	657	322	689	0	673	360	MAND_APPR
6	83	1460	1542	180	684	177	767	27	725	184	MAX_OCCL
7	16	1543	1558	359	693	399	708	0	700	378	0
8	8	1631	1638	434	732	439	739	1	735	434	0

SEG	Y_EXTREMA	X_EXTREMA	ANTE_SEG	POST_SEG	RULE
0	251	578	-500	-500	9
1	94	168	-500	-500	17
2	68	335	-500	-500	17
3	62	497	-500	-500	17
4	60	669	-500	-500	17
5	397	657	-500	-500	12
6	192	729	-500	-500	14
7	399	708	-500	-500	0

Figure 7.7 Classified pixel segments in Level 4 of model.

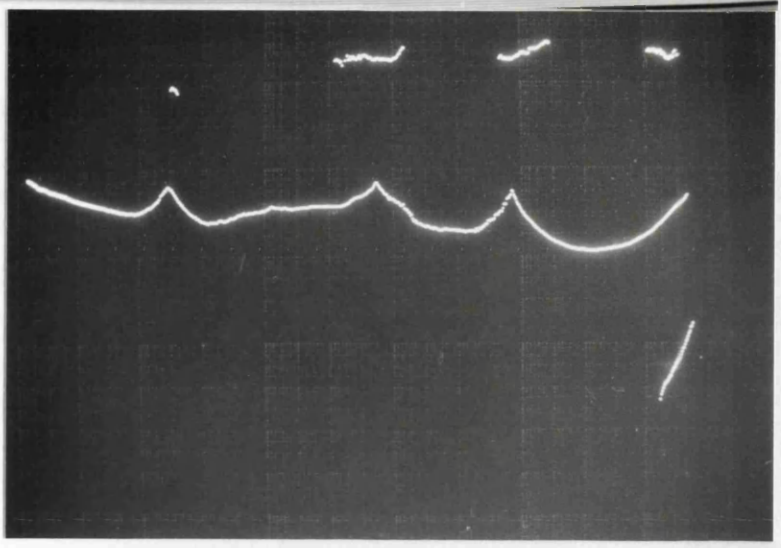


Figure 7.8 Classified maxillary segements of Level 4 shown on monitor.

The actual pixel segments can be seen in Figure 7.8 which are a very long maxillary occlusal segment, 4 maxillary bony crests and a mandibular approximal surface. A small maxillary occlusal surface is listed in Figure 7.7 and can be seen for tooth 13 in Figure 7.9, which contains all the image segments from the total segment table which is only shown partially in Figure 7.7.

The rules can cope with several small segments which are part of larger structures, such as multiple occlusal segments, and link them together. The more that is known about structures, the more confident the classifications become.

Sufficient is now known about the segments that unknown or noise segments can be removed to simplify the recognition problem. In Figure 7.6 the mandibular pixels which were clearly below the alveolar crest margin have been removed by rules which identified these as being subcrestal and in Figure 7.9 they are absent. In addition rules have removed the 4 curved segments at the corners of the film and other noise segments. Some approximal pixels and the inferior surface of the mandibular pontic have also been removed (Figure 7.9).

The information contained in level 4 is sufficient for the computer to "guess" where the interdental spaces are and to search for them (for method see 7.2.7). As a result of discovering the interdental spaces, additional information becomes available for level 5.

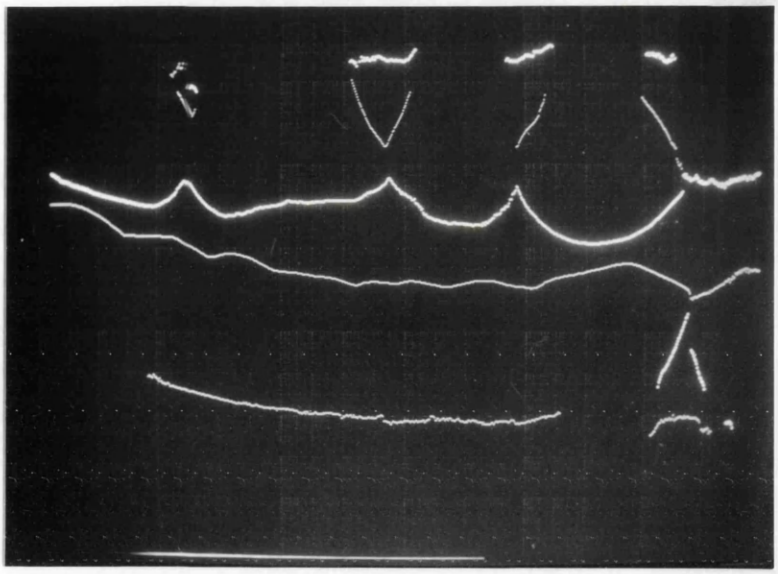
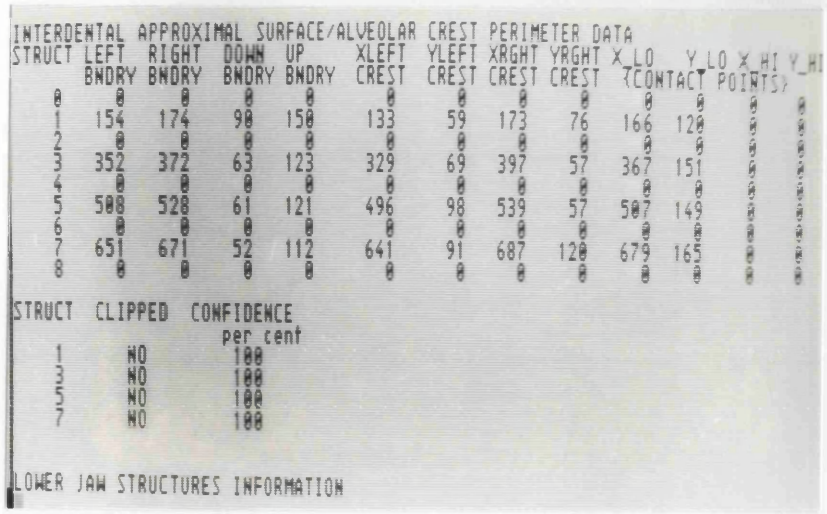


Figure 7.9 All classified segments of model Level 4 displayed on monitor. Bone noise and film corner pixels have been removed.

Level 5 has a spatial scale and information content which is significantly greater than level 4. Level 5 represents a mixture of semantic information (English-like anatomical regions) and spatial information where the regions can be found in the image.

In level 5, lists are found of the X, Y coordinates for the mesial and distal limits of the interdental alveolar crest margins where bone loss may occur (odd numbered structures "STRUCT" in Figure 7.10). In addition the coordinates for the apical portion of the approximal surface contact point overlaps is listed ("X_LO, Y_LO CONTACT POINTS"). This is for future use as a reference point for caries prone regions. There is also listed the confidence values for 4 maxillary interdental spaces which in the example shown are all 100% (section 7.2.4).



INTERDENTAL APPROXIMAL SURFACE/ALVEOLAR CREST PERIMETER DATA

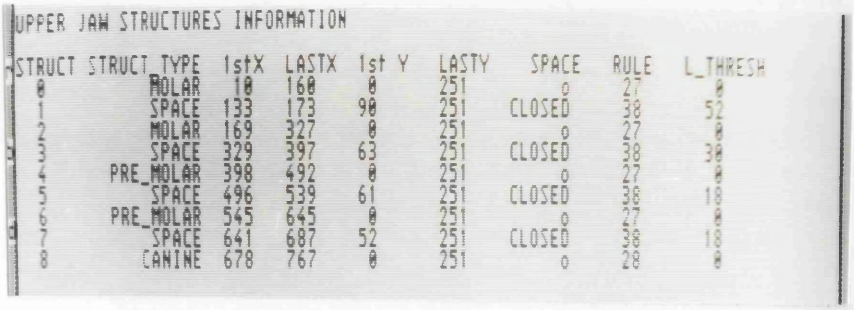
STRUCT	LEFT BNDRY	RIGHT BNDRY	DOWN BNDRY	UP BNDRY	XLEFT CREST	YLEFT CREST	XRGHT CREST	YRGHT CREST	X_LO (CONTACT	Y_LO POINTS)	X_HI	Y_HI
0	0	0	0	0	0	0	0	0	0	0	0	0
1	154	174	90	150	133	59	173	76	166	120	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	352	372	63	123	329	69	397	57	367	151	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	508	528	61	121	496	98	539	57	507	149	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	651	671	52	112	641	91	687	120	679	165	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0

STRUCT	CLIPPED	CONFIDENCE per cent
1	NO	100
3	NO	100
5	NO	100
7	NO	100

LOWER JAW STRUCTURES INFORMATION

Figure 7.10 Spatial information for alveolar crest and approximal overlap regions in model Level 5.

Level 6 lists the spatial coordinates for rectangular regions of the image which contain the crowns of individual teeth and interdental space regions. This is shown in the table of upper jaw structures of Figure 7.11 and lower jaw structures of Figure 7.12. Very little computer processing is required to pass from level 5 to level 6. This is because the processing is primarily concerned with the manipulation of rules on the data created from the lower levels which is only a few bytes.



UPPER JAW STRUCTURES INFORMATION

STRUCT	STRUCT_TYPE	1stX	LASTX	1st Y	LASTY	SPACE	RULE	L_THRESH
0	MOLAR	10	160	0	251	0	27	0
1	SPACE	133	173	90	251	CLOSED	38	52
2	MOLAR	169	327	0	251	0	27	0
3	SPACE	329	397	63	251	CLOSED	38	30
4	PRE_MOLAR	398	492	0	251	0	27	0
5	SPACE	496	539	61	251	CLOSED	38	18
6	PRE_MOLAR	545	645	0	251	0	27	0
7	SPACE	641	687	52	251	CLOSED	38	18
8	CANINE	678	767	0	251	0	28	0

Figure 7.11 Maxillary jaw information from model Levels 6 and 7.

LOWER JAW STRUCTURES INFORMATION

STRUCT	STRUCT_TYPE	1stX	LASTX	1st Y	LASTY	SPACE	RULE	L_THRESH
0	PRE_MOLAR	10	119	210	574	0	27	0
1	PONTIC	124	549	210	388	CLOSED	38	26
2	PRE_MOLAR	552	648	210	574	0	27	0
3	SPACE	651	709	210	441	CLOSED	38	24
4	PRE_MOLAR	716	767	210	574	0	28	0

Figure 7.12 Mandibular jaw information from model Levels 6 and 7.

Level 7 is the highest in the model and similar to level 6, requires almost no processing time due to the reduction in data volume. The model is split into upper jaw (Figure 7.11) and lower jaw (Figure 7.12). The anatomical structures are classified not just into teeth and spaces but also into subtypes. In the case of teeth, these are big molars, molars, premolars, canines and small teeth. Interdental spaces can be closed or open into the interocclusal space. A bridge pontic is a type of closed space.

The position of the structures in the table tells you about their spatial relationships in relative terms. In Figure 7.11 the first structure in the upper jaw is a molar which is left of the canine in the image, although listed vertically in the table, and separated by 3 other teeth. Since the order is molar, molar, premolar, premolar and canine it is not difficult to deduce that this must be a right bitewing.

This information is very powerful because it can be used to correct errors of classification. In Figure 7.12 the model is incorrect in classifying tooth 47 as a premolar. The error is due to the width of the tooth appearing to be the same as a premolar, resulting from the edge of the film cutting across the tooth. If a rule had been applied

to the model to check for the consistency of individual tooth classification, it would have immediately have found an error. This would have been caused by a probability of almost zero for the mandibular tooth at the left edge of the image being a premolar compared to the classification of the other teeth. In many ways, this approach mimics the activity of junior dental students but as clinicians become experienced, the method probably becomes subconcious.

7.2.7 Automatic identification of interdental spaces

The information, contained in level 4 of the model, indicates to the program where the interdental spaces are likely to exist.

The interdental spaces are found by the program performing a limited horizontal and vertical cross-wise search based on a previously classified alveolar crest margin segment. As each branch of the cross is traversed, the program records the position of the pixel with the lowest grey level, assuming this to be the centre of an interdental space.

The computer then begins a search of the interdental space by grey level contouring, to establish the perimeter outline of the approximal tooth surfaces and the alveolar crest margin. A grey level contour is similar to the lines of height found on an Ordnance Survey map. To reveal the computer search, the contour paths are marked by white pixels. These are only to reveal the computer actions to a human

observer and are unnecessary for the construction of a model.

Since the first contour is unlikely to be the correct outline of the required structures, 10 contours are explored. A series of rules are applied to the contour tracks to test for straightness, backtracking (reversing the search path on itself) and changes between tracks to find the correct perimeter.

In the current version of the program, if a track does not satisfy the rules, no perimeter is displayed on the screen. The perimeter tracking method is still under development and is not involved in the construction of the model. It has been described only since it graphically portrays that the program has found the interdental spaces.

7.2.8 Testing of automatic model creation

The success of the program to create a model of the image can be judged by its ability to automatically find the interdental spaces, since the model depends on this.

Thirty-one clinical bitewing films were picked at random from 2 groups of films. One group of 15 films were produced by a radiographer (Group I) and the other 16 films by a radiologist (Group II).

Each film was placed into the film carrier of the equipment described in section 5.2. The camera position was set so that a number 2 sized

film filled the whole screen at a pixel size of 0.05 x 0.05 mm. The magnification was times 6 and the camera gamma 0.45. The back illumination from the light box was constant. However, the camera aperture and video amplifier gain were adjusted so that the approximal tooth regions were just below saturation level (about 250 grey levels). No further adjustments were made and the program initiated in automatic mode.

All the stages of image processing proceeded without any human operator involvement until completion which took 2 minutes. While the program was operating, a record was kept by the operator for each interdental space. The space was judged to have been identified if a grey level contour search was visible as a series of white tracking lines (Figure 7.13), even if at the end of processing, the rules rejected all the tracks.

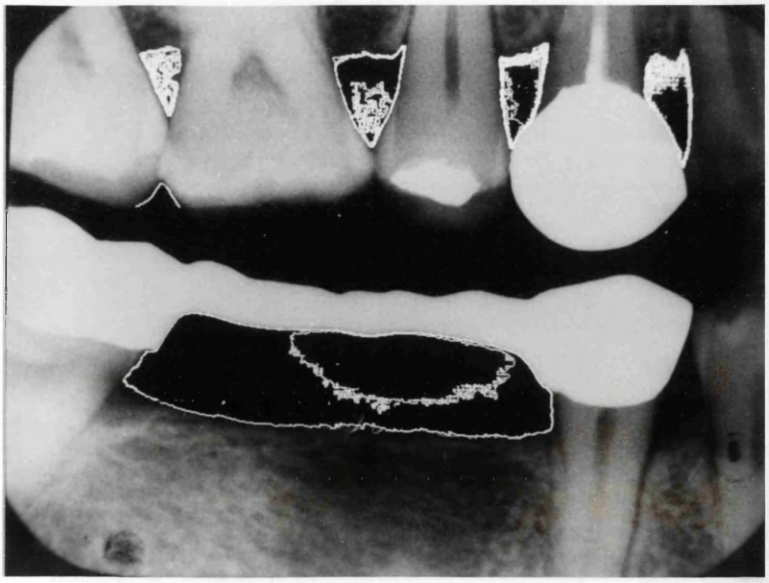


Figure 7.13 White pixel tracks from interdental space searches.

In the example shown, all the interdental spaces had a search track accepted by the program rules, which is displayed as a white path along the interdental alveolar crest margin and approximal tooth surfaces (Figure 7.14). Notice how the path delineates calculus on the distal surface of tooth 16.

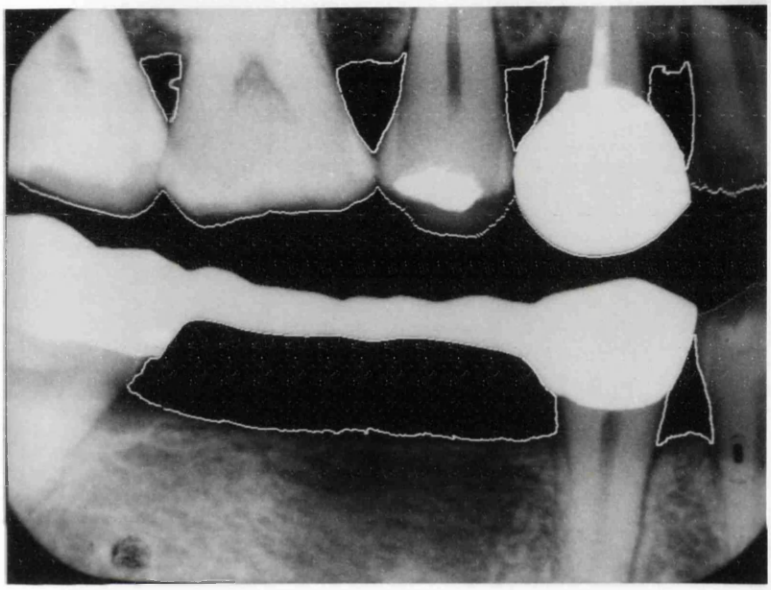


Figure 7.14 Automatic delineation of interdental alveolar crest margins and approximal tooth surfaces.

The reproducibility of finding 34 interdental spaces was tested, by capturing a second digital image from 5 films, without altering the camera amplifier or aperture settings.

7.3 Results

From a total of 208 interdental spaces available in 31 bitewing radiographs, the computer without any human guidance found 193 or 93% of the spaces. Out of 31 films, the computer found all the available

spaces in 21 images or 68% of the films.

When the films were analysed according to their group of origin, the findings were different. In group I, 84 out of 98 (86%) of the possible interdental spaces were identified and only 6 from 15 (40%) of films had all the available spaces found (Table 7.1). In group II, 109 out of 110 (99%) of the spaces were found and 15 out of 16 (94%) of the films had all the available spaces found (Table 7.2).

The reproducibility test showed that from a maximum of 34 spaces available, 33 (97%) were identified from the first images compared to 32 (94%) with the second; a change of only 1 space (Table 7.3).

Table 7.1 Automatic identification of interdental spaces for Group I bitewing radiographs.

Film	Spaces present	Spaces found
1	6	2
2	6	*6
3	6	5
4	6	*6
5	5	*5
6	6	5
7	8	6
8	6	*6
9	8	7
10	7	*7
11	7	6
12	7	6
13	7	*7
14	7	6
15	6	4
	98	84

86%

40% film all sites

Key: * = all sites identified

Table 7.2 Automatic identification of interdental spaces for Group II bitewing radiographs.

Film	Spaces present	Spaces found
16	8	*8
17	7	*7
18	8	*8
19	7	*7
20	7	*7
21	5	*5
22	6	*6
23	8	*8
24	7	*7
25	6	*6
26	7	*7
27	6	*6
28	7	*7
29	6	*6
30	7	*7
31	8	7
	110	109

99%

94% film all sites

Key: * = all sites identified

Table 7.3 Reproducibility of automatic identification of interdental spaces.

Film	Spaces present	Spaces found	
		1st image	2nd image
27	6	*6	*6
28	7	*7	*7
29	6	5	5
30	7	*7	*7
31	8	*8	7
	34	33	32

Key: * = all sites identified

7.4 Discussion

The variation in results between groups I and II are quite striking, considering the computer examination method was identical. There was however, a difference in the irradiation technique with group II films having minimal approximal overlapping, producing large interdental spaces. In group I the film positioning was consistently poor, causing small interdental spaces. The group II films were exposed by a radiologist and group I by a radiographer. Both operators used the author's repositionable film holder (Appendix V) but the radiographer misunderstood the positioning instructions, which caused consistent excessive approximal overlapping. It would appear from the results that the automatic method works very well with correctly positioned films, but has more difficulty finding small interdental spaces.

The reproducibility results were good with a change of 1 space out of 34 between repeat examinations.

In considering the performance of the computer program, it should be remembered that this is not a completed system but a feasibility study into the development of completely automated diagnostic and monitoring techniques. The results are very encouraging since the films used were clinical radiographs and not simulations. The full clinical range of images were encountered with caries free teeth, healthy alveolar crest margins, minimally restored teeth, crowns, bridges and partially edentulous ridges.

The processing time of approximately 2 minutes to create an image model is rapid compared to the manual systems which can take up to 60 minutes for one film (section 7.1). Although the automatic method was not yet making measurements or comparisons between serial films, this would only add about 10 seconds to the processing time, since most of this period is required for constructing the image model.

The current findings seem to support the initial decision to use interdental spaces as the key image features to be identified. Further work is required to raise the recognition rate to 100%, especially for films with substantial tooth surface overlapping. This will probably require an extension of the knowledge-based rules rather than lower level image processing.

All the bitewing images in this study had their occlusal planes parallel to the long axis of the film. This was ensured by the use of the repositionable film holder which guaranteed the correct orientation. If bitewing paper tabs were used and applied incorrectly to the film packet producing an inclined occlusal plane, the automatic method would probably fail as it expects a near horizontal orientation. However, this is not a serious limitation since in practice, one should not be trying to use accurate measuring methods without standardized irradiation geometry (section 4.3.2.4 and Appendix IV).

Additional investigation is needed to determine whether alterations in the viewing box illumination will affect the accuracy of the image

model. Changes in illumination are unlikely to affect model accuracy since it does not depend on a linear relationship between regions of different optical density in the film. As discussed previously (section 4.6.1) a low camera gamma is required to separate similar regions of optical density at the dark end of the grey range. The gamma value of 0.45 used in this work, definitely produces a non-linear video signal response to changes in light intensity. Although this aids the detection of dark regions of bone, a change in illumination with this gamma setting is more likely to affect densitometric measurements rather than model construction.

Before contemplating adding diagnostic/ monitoring modules to the automatic recognition method, the effects of siting the system in a general practice should be investigated, since this is likely to modify the design of the user interface.

7.5 Conclusions

A method for automatic image recognition of bitewing radiographs has been developed. The results of initial testing are very encouraging but further research is required before 100% reliable image models can be automatically created and used to guide measuring methods.

Chapter 8 General discussion

There are no reliable predictors for initial caries attack or periodontal destruction (sections 3.2.2, 3.3.9, 3.4). This emphasises a need for accurate diagnostic tests. Unfortunately all the existing traditional clinical methods are inaccurate (sections 3.5.4, 3.7, 3.8). However, based on criteria of validity, reliability and ease of use, intra-oral radiography was identified as the best available technique for detecting early approximal caries and interdental alveolar bone crest changes (sections 4.4, 4.6.3, 4.6.5, 4.7).

The principal limitations of radiography for diagnosing and measuring dental disease are due to :-

i) irradiation geometry variation between serial films which can affect the validity of radiographic images.
ii) subjective errors in film evaluation and measurement.
iii) operator time in making measurements.

The contribution of the experimental work contained in the thesis will be discussed in relation to these limitations.

8.1 Irradiation geometry

A detailed in vitro investigation was performed on the effects of irradiation geometry changes and the validity of bitewing images of precavitated approximal lesions (Appendix IV). The research revealed

that very shallow precavitated approximal lesions can be seen on bitewing films, but these images can be lost if the X-ray beam varies in the horizontal plane >= $\pm$ 3 ^{o} between serial films.

Previous studies have shown that irradiation geometry can alter images (Leijon 1969; Stoner 1974; Sewerin 1981, 1983, 1987; McDonald 1984; Hausman et al 1989a). However, no studies have used histologically validated precavitated caries-like lesions to test the effects of irradiation geometry changes on the radiolucencies. Contrary to established teaching (Gwinnett 1971; Silverstone 1982), a significant proportion of very shallow approximal white spot lesions may produce detectable radiolucencies although magnification will be required to see them (Appendix IV). Since the purpose of designing more accurate systems is to detect lesions at the earliest possible stage, this investigation has shown that researchers may be incorrectly assuming that radiography is unable to record shallow lesions and are failing to exploit a valuable technique.

Tooth crowns are not composed of geometrically planar surfaces. For any particular X-ray beam orientation perhaps only a minority of posterior approximal surfaces will be favourably inclined to produce maximum radiographic sensitivity for small lesions. Nevertheless, if the irradiation geometry can be maintained between serial films, the earliest diagnosis and monitoring of disease becomes a possibility for the favourably inclined surfaces. The key to early diagnosis is the control of irradiation geometry followed by the use of accurate measuring systems.

The need to standardize irradiation geometry led to the development of a repositionable bitewing holder, which is reported in Appendix V. The results of initial testing of patient tolerance to the holder are favourable with 88% (n=100) of the patients finding the device neutral or comfortable. A high degree of positioning reproducibility was achieved with 6 out of 8 pairs of films maintaining an approximal overlapping measurement to <= $\pm$ 0.15 mm for the small number of test films. A large scale evaluation of the holder is in progress with the Royal Navy.

Although the effectiveness of the film holder design has not yet been proved, it is important to stress that standardised irradiation geometry is essential for producing valid image comparisons.

8.2 Digital subtraction radiography

Digital subtraction radiography is a recent imaging technique for investigating alveolar bone crest changes. Images can be viewed subjectively, for diagnosing disease changes, or objective measurements can be made related to grey levels or aluminium equivalents. A literature search revealed that between 1982 and November 1990, 47 papers were published. Since so much dental research activity and resources are being expended on research utilising this technique, it seemed important to evaluate the method further. In particular the problems associated with manual positioning of a subsequent film for image subtraction. Grondahl et al (1984)

examined the relationship between subtraction errors and irradiation geometry changes. However, no previous studies have investigated in detail the effects of manual misalignment of a subsequent film on the production of false subtraction values.

The validity of the images produced by the digital subtraction radiography technique were experimentally investigated in Chapter 6. It was shown that very small errors in positioning films, under a video camera, could result in subtraction errors which could be incorrectly interpreted as disease changes. Almost a half of all subtracted crestal pixels examined, with a 0.3mm vertical displacement between identical images, had a false grey level change of at least 4.1% of the grey range (Table 6.5 Appendix III). Even though mechanically driven film carriers could be used which are easily capable of stepping at 0.1mm intervals, the problem is in determining the "correct" position for subtraction. Up to 40% of serial radiographic film pairs from a clinical study have been rejected as unsuitable for comparison by the digital subtraction method (Hausemann et al 1988), indicating a considerable problem in the production of standardized films. Since subtraction errors can originate from different causes (section 4.6.4.2) it is possible that errors are compound and complex. A bending of the corner of one film would lead to local errors in that region of a subtracted image. Any attempt to minimise the corner error by altering the position of the subsequent film, beneath a camera, would introduce new errors in other sites of the image as shown in Chapter 6. The camera misalignment errors would be in addition to any others caused by irradiation geometry variation.

At any particular subtracted image site, it is impossible to know which grey level changes are real or due to subtraction errors. Only if a subtraction image has lost nearly all the anatomical outlines can it be considered to be well standardised and subtracted "patches" represent valid tissue changes. Unfortunately these are rarely produced by this technique and misalignment banding errors, of the type demonstrated in Chapter 6, can be seen in many papers (Webber et al 1982; Grondahl and Grondahl 1983; Grondahl et al 1983; Lurie et al 1983; McHenry et al 1987; Bragger et al 1988b; Ohki et al 1988; Schmidt et al 1988).

Although methods were suggested (section 6.4) for estimating the size of the likely errors at each image site, this would decrease the sensitivity of the method. The high risk of producing artificial image changes coupled with extreme difficulty in producing absolutely standardized images, would seem to suggest that subtraction radiography is not a useful technique for detecting small valid changes between serial films.

8.3 Stored region of interest measurement method

The reliability of subjective linear measurements made from enlarged radiographic images ranged from SD 0.02 mm to 0.47 mm (section 3.6.4). The objective method of Pitts (1984a) was very reliable with retest variation of $\pm$ 0.03 mm. However, all the methods were very time consuming and only 2 out of 9 techniques used digital images (Pitts 1984b; Hausman et al 1989).

The stored region of interest (ROI) method developed in Chapter 5 performed well with a wide range of different examiners attaining SD 0.15 mm intra-examiner variation between repeat readings. Since the system is easy to use and measurements rapid to make, it was possible to design a method where every measurement is duplicated by the operator. This allows the automatic calculation of 90% confidence values for changes found between sites in serial films which is a unique feature for a subjective method. Only Al-Kufaishi et al (1984) reported more reliable measurements which are probably due to the use of the image border of a Backer-Dirks holder as one measurement reference site. The high contrast of the holder border is far easier to identify than a hard tissue reference point. This effectively reduced the measurement variation to only the alveolar crest site. In addition the image was not digitized and only one trained examiner performed the measurements which would again improve the reliability.

The effectiveness of the influence on an examiner from the stored ROI method, can be judged by the low inter-examiner variation of SD 0.22mm for 13/14 test sites. The standard examiner image reference points, which all the other examiners were asked to copy, were deliberately made to be highly atypical to reduce the likelihood of random selection. Points at 2-3mm apical to the alveolar crest margin where chosen either in cancellous bone or in the cribriform plate of the periodontal ligament space. This required the clinicians to "navigate" by eye using trabecular patterns in the ROI and to identify similar points in the test region. The small differences in the points chosen

by the examiners, compared to the target reference points, showed how effective the stored ROI method was in guiding examiners to a specific point in an image.

Despite being a subjective method, the stored ROI should be of value in investigating structural trabecular bone changes, such as the loss of individual plates or rods between serial radiographic images which has not been previously performed. This is because trabecular bone images are complex and no simple method was available for identifying specific bony features. In addition to measuring bone, the standardization of irradiation geometry between serial films can be tested by measuring the constancy of the dimensions of approximal surface overlap (Appendix V).

The stored ROI method is a flexible and very reliable subjective method for measuring tooth and bone changes between serial films. It can be used for detecting irradiation geometry changes between films which might invalidate comparisons and also provides a confidence value for each measured change.

8.4 Automatic image analysis

Although accurate objective measurement methods have been developed for detecting early changes in approximal caries (Pitts 1984a) and alveolar bone crests (Payot et al 1987a), time consuming initial human interaction is required. Time is expensive in research laboratories and in general practice. Therefore a need was felt to investigate a

method for automating computer measuring systems. From a very lengthy period of software development, an automatic method was developed to create an image model as the first step required to replace a human operator (Chapter 7). The method was successful in automatically finding 93% of all available interdental spaces in 31 clinical bitewing films, indicating that automation should be feasible. This compares favourably with an 80% success rate in identifying 5 anatomical points in cephalometric radiographs using an automatic method (Davis and Taylor 1990). Their sophisticated general purpose system required several hours of processing for each image. In contrast, the automatic bitewing method required only 2 minutes of processing time as it is specifically designed for analysing bitewing radiographs. This demonstrates the relationship between computer time and the possible range of images which can be analysed. A computer system which could analyse intra-oral, skull and dental panoramic films would require a large amount of knowledge and processing time. Currently no computer systems have this degree of "general purpose" image recognition although the Manchester University research group (Davis and Taylor 1990) are investigating these problems.

8.4.1 Potential limiting factors of automatic image analysis

8.4.1.1 Image recognition success rate

To be clinically useful, automatic systems need a very high success rate for image recognition, since failure requires additional operator interaction to correct errors. If correcting errors needs a

complicated or unfamiliar procedure to be performed by an operator, a high degree of training may be required. It is not possible without proper clinical trials to decide what is an acceptable success rate but 95% or higher is probably realistic, depending on the amount and type of operator action required.

Despite the encouraging overall score of 68% of the test films having all their interdental spaces correctly found by the automatic computer program (section 7.3), this is far below the target of 95%. Although it is anticipated that automatic recognition can achieve the target, a limited degree of operator interaction could be accepted providing it required less than 10 seconds per film and was simple to perform. The use of a mouse to mark interdental spaces in an image could be a quick and simple method, considerably reducing the task of constructing an image model and ensuring 100% correct model construction.

8.4.1.2 Film X-ray sensors

The production in general practice of high quality radiographic images, suitable for image analysis, may be a considerable problem. Only about 10% of radiographs reach a high standard of technical excellence, while 50% have a low contrast range and diagnostically are of limited value, usually due to poor chemical processing (Dental Practice Board 1990).

An additional problem can be caused by incorrect handling of film leaving scratches or finger prints on the surface resulting in

measurement errors with sensitive computer systems (Pitts 1984a). One must assume that if Pitts encountered difficulties in using radiographic trial data, produced and stored under ideal conditions, the risks of errors arising from damaged general practice film will be higher.

8.4.1.3 Solid state X-ray sensors

It is possible that the success of accurate computer measuring systems will depend on the replacement of film by intra-oral solid state X-ray sensors. Fortunately, early versions of these devices are already in clinical use (RadioVisioGraphy, Trophy, Paris) preventing the errors arising from chemical processing and handling. Existing solid state sensors are too small to capture bitewing images (section 4.3.1.3), larger sensors are needed.

It is tempting to suggest that improved manufacturing techniques will produce larger sensors and the capture of solid state bitewing images is assured. Unfortunately the rigidity and extra thickness of solid state devices, compared to film, may cause additional problems with regard to patient tolerance. Gratt et al (1978) tested patient tolerance to xeroradiograph cassettes simulated by periapical film, thickened to 3 mm with rigid acrylic plates. They reported that out of all the possible intra-oral projections, the posterior premolar bitewing and mandibular premolar periapical projections were least well tolerated by patients compared to film. Gratt et al (1978) suggested the patient discomfort could be prevented by rotating the

anterior edge of the cassette towards the midline but the possible changes in image distortion and diagnostic validity were not considered. Since Gratt et al used paper loops to hold their cassettes in the bitewing position, and not a rigid beam aiming device, a cassette held in an ideal irradiation geometry orientation might be more uncomfortable than their study suggests. It remains to be seen if large rigid solid state detectors will be tolerated as well as their film equivalents.

8.4.1.4 Operating time

Image sensor resolution

Pitts (1984a) required a magnified image with an effective pixel size of 0.03 mm by 0.03 mmm. For most modern CCD cameras with a sensor resolution of approximately 600 by 575 pixels, this would produce an enlarged monitor image limited to one quarter of the original film area to achieve such a small pixel size. The ideal monitor image should contain the complete film area, as this would remove the time needed for an operator to reposition a film 3 times beneath a camera to cover the entire film surface. Cameras are available with sensor resolutions of 1300 by 1000 pixels (Kodak, Hemel Hempstead) which would satisfy the requirements, but are expensive at £17,000. Nevertheless, as prices fall it should be possible to use cameras of a higher resolution which will reduce operator time.

Software

Larger, high resolution, images also contain more pixels and a doubling of resolution results in a quadrupling of image memory. For conventional software which operates predominately on pixel grey levels, an increase in image memory will produce a proportional increase in processing time (Gonzalez and Wintz 1987). A program which takes 2 minutes to analyze a bitewing image will require an extra 6 minutes for a four fold increase in image memory. Instead of taking 4 minutes to process 2 films per patient, 16 minutes will be needed which will remove most of the operator time saved by using the higher image resolution. However, if a model based image analysis method is utilized, which spends only 20 seconds processing the pixel grey levels out of the total 2 minutes computing time, a quadrupling of the image memory will only increase the program time by about 60 seconds to 3.0 minutes.

In designing an automatic analysis method, all components of the system must be examined for predicting the outcome in altering individual elements. In this particular example, the data compression from the hierarchical image processing method does significantly reduce the processing time compared to conventional image processing approaches.

8.4.1.5 Summary of automatic image analysis

The successful demonstration, of an image modelling technique, is an

advance which indicates that completely automatic image analysis of bitewing radiographs may be possible. No previous methods have been reported for automatic model construction of bitewing images although similar work on skull radiographs is in progress (Davis and Taylor 1990).

8.5 Future research

Further research should be performed in three main areas:-

i) A better understanding of early disease changes is required to provide a guide to radiographic changes which can be expected to be seen. The lactic acid gel model (Silverstone 1984) is very suitable for caries studies where the effects of various agents on radiolucencies, such as fluoride, can be investigated. It is very important to know if reduction in the size of a carious radiolucency always means that demineralization in the depth of the lesion has ceased. If it has not ceased are there any characteristics in the radiolucency which can provide a guide to lesion activity, such as bands of different optical density at various lesion depths? Carefully designed in vitro experiments may provide some of the answers. However, crude models, such as drilling small holes in teeth, always run the risk of providing false information which can hinder rather than advance scientific knowledge. Van der Stelt et al (1989b) performed an investigation regarding the validity of approximal carious lesions and irradiation geometry changes. Unlike the work reported in Appendix IV, which examined shallow caries-like lesions

formed from lactic acid gels, Van der Stelt et al drilled holes 0.24-0.63mm deep into approximal enamel producing uniform hemispherical high contrast radiolucencies. These lesions were reported as having a tolerance range of $\pm 7^{\circ}$ horizontal X-ray beam change for optimal detection. This conflicts with the findings (Appendix IV) of $\pm 3^{\circ}$ limit for maintaining a radiographic score. The greater sensitivity of the latter work to horizontal X-ray beam changes, was probably due to the artificial white spot lesions which were elongated in the bucco-lingual direction similar to natural lesions. Here is an example of different results being produced from disimilar caries models.

The existing laboratory methods of simulating alveolar bone loss by drilling holes in bone probably do not truly represent disease change. More effort is needed to develop models capable of undergoing widening of bony vascular canals and perforation of trabecular plates which may occur in the early phases of periodontal bone destruction. Models suitable for radiography must also include soft tissue substitutes, such as epoxy resins, since dry empty bones form images of artificial high contrast and resolution of edge structures. Techniques have been developed for perfusing dry mandibles with epoxy resin to form life-like images capable of simulating small scale bony changes (Benn et al 1990).

ii) Although in vitro work is important as an initial guide to tissue changes, there is no substitute for clinical observation. Frequent observations over weekly intervals of hard tissue changes have not

been performed previously for ethical and technical reasons.

The primary ethical reason has been the risk to the patient of ionising radiation. However, if highly collimated X-ray beams (2cms diameter) were used in conjunction with rare earth beam filters and "E" speed film, the absorbed dose to the patient can be reduced by 40 times or more compared to conventional "D" speed bitewings. Certain high risk category patients for developing alveolar bone loss, such as insulin dependent diabetic patients, could ethically benefit from frequent low dose examinations. Especially if the early detection of bone change resulted in successful treatment. The research benefit would be to provide short time interval monitoring, say once a week for 5 weeks, which could provide unique information concerning physiological and pathological bone changes.

The technical difficulties of making reliable measurements of bone trabeculae could be overcome by using the system developed in Chapter 5, subject to initial in vitro validation. Epoxy resin perfused dry mandibles have already been prepared for this purpose (Benn et al 1990).

Clinical studies are already in progress, using the stored ROI measuring system, in a collaborative study to evaluate a toothpaste additive for its effect on the rate of alveolar bone loss.

iii) The work of automating image analysis of radiographs should be continued, since it will reduce the costs of examining and comparing

large numbers of serial films.

Chapter 9 General conclusions

1. There are no reliable predictive tests for the initial onset of dental caries or the periodontal diseases. This emphasises the need for accurate diagnostic tests but unfortunately, all the existing traditional clinical methods are inaccurate.

2. The best method for diagnosing dental diseases based on the criteria of validity, reliability and ease of use is radiography. It was chosen from the available methods primarily because objective data is produced which can be measured by a variety of techniques.

3. Bitewing radiographs provide the best method for detecting approximal caries although they have a low sensitivity for occlusal caries. However, there is recent evidence to show that visual identification of occlusal caries has become more difficult, reinforcing the importance of radiographic examinations.

4. Bitewing radiographs also offer the best opportunity for detecting early interdental alveolar bone crest margin changes. Radiography is the only method available for revealing structural bone changes.

5. Radiography does suffer from the disadvantage of using ionising radiation which necessitates infrequent periodic examinations to reduce the absorbed patient dose. This restricts radiography to revealing the history of disease changes rather than the presence or absence of current disease activity. Suggestions have been made for

developing short time interval radiographic monitoring for high risk subjects.

6. Irradiation geometry changes can affect the validity of images and standardized positioning is essential. A repositional bitewing film holder suitable for general dental practice was developed and limited testing produced favourable results. Large scale trials are in progress. The aim of the device is to improve the validity of radiographic images.

7. A very reliable method for making linear radiographic measurements has been developed and tested.

8. A new methodological problem was revealed when evaluating the digital subtraction method. This adds further evidence to the known deficiencies of the technique which suggests that digital subtraction radiography is not a useful research or clinical tool for dental disease.

9. A new artificial intelligence method was developed which indicated that completely automatic analysis of bitewing images may be possible, facilitating the routine use of accurate diagnostic methods.

This thesis has identified radiography as currently the most useful diagnostic method. Those areas which affect the validity, reliability and measurement of features in radiographic images have been identified and methods developed to improve them.

Further research should be performed in :-

i) Developing better in vitro radiographic periodontal disease models.
ii) Investigating the use of frequent low dose radiographic examinations on high disease risk patients.
iii) Developing an automatic image analysis method.

Appendix I DEFINITION OF SOME COMMON SENSITOMETRIC TERMS

Density

Photographic density is the degree of blackening which occurs when a film is exposed to radiation.

$$D = \log_{10} (L_i / L_t)$$

where D = optical density.

Li= incident light intensity on film.

Lt= transmitted light intensity from film.

Contrast

Objective contrast is the measured difference in density of adjacent areas on a film.

Subjective contrast is the visual appearance of density differences which are important in the interpretation of radiographs.

Film contrast is a measure of the slope or steepness of the characteristic curve of a film which is dependent on the emulsion, film processing and density produced.

Speed

Speed is an indication of the amount of radiation required to produce a radiographic film of standard density, usually optical density 1.0

above base and fog.

Speed can also be referred to as the reciprocal of the exposure needed to produce a given net density. A faster film requires less exposure than a slower film to produce a given density.

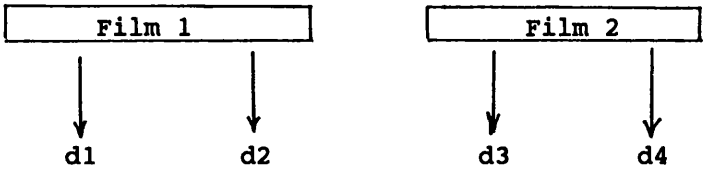
Resolution

Resolution or sharpness is the ability of a film to distinguish as separate entities 2 image features which are close together. A grid of alternate light and dark bands of varying thickness is often used to describe film resolution in terms of line pairs per mm or lp/mm.

Appendix II CALCULATION OF CONFIDENCE VALUE OF MEASUREMENTS MADE IN METHOD OF CHAPTER 5.

Acton (1959) developed a theory that a series of straight line measurements could be considered to be part of a population of possible measurements. The range of measurement errors, providing they were random and not subject to a systematic bias, should have a normal distribution. Acton proposed that the difference between successive measurements could be used for estimating where a subsequent measure value would be likely to fall. From tables calculated by Acton (1959) it is possible to estimate the chance of a measurement falling within a certain range of values. For a pair of duplicate measurements, in this case repeated distance measurements on the same radiograph, if the average distance is multiplied by 3.2 then all subsequent measurements have a 90% chance of falling within this range. Consequently if a distance is greater than this range then there is a 90% chance it is due to a real change in measured distance and only 10% likely to be due to measurement error.

Calculations



me1 = d1-d2 me2 = d3-d4

l1 = (d1+d2)/2 l2 = (d3+d4)/2

mea = (me1 + me2)/2

dc = l1-l2

If dc > (mea x 3.2) then dc has > 90% confidence of true measured change.

Key: dn= distances measured; men= measurement error per film ; ln= average distances per film; mea= average of measurement errors; dc= measured change between films.

Appendix III CHAPTER 6 TABLES.

Table 6.1 Displacement between identical digital images prior to subtraction. The displacement distance is based on pixels of length 0.05 mm in the X or Y direction and 0.07 mm if both X and Y have non-zero values eg X=4 Y= 0 is a horizontal displacement of 0.2 mm while X=4 Y=4 is an oblique image displacement of 0.28 mm

Figure	Displacement in pixels		Distance
	X	Y	(mm)
6.3	0	0	0
6.4	2	0	0.1
	4	0	0.2
	6	0	0.3
6.5	-6	0	-0.3
6.6	0	2	0.1
	0	4	0.2
	0	6	0.3
6.7	0	-6	-0.3
	2	2	0.14
	4	4	0.28
	6	6	0.42
	-6	-6	-0.42

Table 6.2 Distribution of grey values in a crest region. Sample between teeth 25,26 in subtracted image produced by a vertical displacement of 0.1 mm between original and copy image - Figure 6.6.

Grey value range	Total pixel count	Crest area %	Cummulative area total %
0-115	0	0.0	0.0
116-117	0	0.0	0.0
118-119	0	0.0	0.0
120-121	0	0.0	0.0
122-123	0	0.0	0.0
124-125	32	8.6	8.6
126-127 *	42	11.2	19.8
128-129	62	16.6	36.4
130-131	50	13.4	49.7
132-133	43	11.5	61.2
134-135	55	14.7	75.9
136-137	44	11.8	87.7
138-147	46	12.3	100.0
148-255	0	0.0	100.0

Pixels in sample region n= 374

* Nil change grey levels. Grey range 0-255 analyzed in bands of decreasing grey resolution towards ends of spectrum.

Table 6.3 Proportion of crest area according to subtraction grey level band deviation from nil change value of 127. Band 2 contains grey levels which are ± 6 grey levels from the 126-127 values or ± 2.4% of the total grey range of 256 levels. Fifty percent of the pixels in the crest region area examined in this example have a false value of <= ± 2.4% of the mean. Band 3 reveals that 26.5% of the pixels show a false density change which is in the 2.5-4.0% grey range. This table is derived from Table 6.2 and crest region between teeth 25, 26 in Figure 6.6.

Grey band number	Band ranges grey levels	Band deviation from nil change 127 ± % total grey range	Area of band % Crest Area
1	126-127 *	0	11.2
2	120-125, 128-133	1.0 - 2.4	50.0
3	116-119, 134-137	2.5 - 4.0	26.5
4	106-115, 138-147	4.1 - 7.9	12.3
5	86-105, 148-167	8.0 - 15.7	0.0
6	66- 85, 168-187	15.8 - 23.5	0.0
7	36- 65, 188-217	23.6 - 35.3	0.0
8	0- 35, 218-255	35.4 - 50.0	0.0

* Nil change level 127 in grey band 1.

Table 6.4 Proportion of subtracted crest areas with grey level deviation >= ± 2.5% of total grey range. The extent of the grey level deviation of pixel values from the nil change 127 value in subtracted images can be judged by applying a theshold to the deviation and recording the number of pixels which equal or exceed this value. These pixels can be expressed as a percentage of the crestal image area sampled allowing a comparison between images for different image displacements. A deviation threshold of >= ± 2.5% of the total grey level range 0-255 about the nil change grey level 127 has been used. The mean and SD of the percentage of the crest area with pixels above the threshold are shown for different image displacements.

	Direction and distance of displacement between images								
	X			Y			XY		
(mm)	0.1	0.2	0.3	0.1	0.2	0.3	0.14	0.28	0.42
Mean (%CA)	9.0	15.5	26.1	20.3	49.9	62.8	26.4	49.7	62.2
SD	4.5	8.4	9.7	11.0	15.3	17.2	12.2	18.8	16.6

number of crests n= 21

%CA = per cent of crestal image area

Displacement between images is 0.05 mm x no. pixels in X or Y direction and 0.07 mm x no. pixels in X and Y direction.

Table 6.5 Proportion of subtracted crest areas with grey level deviation >= ± 4.1% of the total grey level range. The mean and SD of the percentage of the crest area with pixels above the threshold are shown for different image displacements.

	Direction and distance of displacement between images								
	X			Y			XY		
(mm)	0.1	0.2	0.3	0.1	0.2	0.3	0.14	0.28	0.42
Mean (%CA)	1.9	5.9	11.7	4.5	27.3	46.1	8.7	27.7	45.9
SD	1.9	6.2	8.3	5.1	15.4	18.2	7.6	17.3	20.8

number of crests n= 21

%CA = per cent of crestal image area

Displacement between images is 0.05 mm x no. pixels in X or Y direction and 0.07 mm x no. pixels in X and Y direction.

Appendix V THE DEVELOPMENT AND INITIAL TESTING OF A STENTLESS REPOSITIONABLE BITEWING FILM HOLDER.

V.1 Introduction

The effects of alteration of irradiation geometry on the diagnosis of dental disease has been reviewed in section 4.3.2.4 and experimentally investigated in Appendix IV. Valid changes between radiographic images are dependent upon consistent irradiation geometry in serial films. However, valid images are not necessarily distortion free, since to achieve geometric perfection in a clinical situation is almost impossible. In order to achieve this, the following conditions would need to be met.

Firstly, the film should be maintained as a flat plane with no bending of the corners from contact with the palate, mandible or pressure from the tongue. Barr and Gron (1959) demonstrated, using cast palates from 150 adults, that the ideal of true parallel periapical film placement is unlikely to be achieved as a routine technique throughout the maxilla.

A number 2 size periapical film placed in the horizontal posterior bitewing position only projects approximately 16 mm above and below the occlusal plane. Nevertheless the film is still likely to contact the palate and bend under pressure if it is close to the palatal surfaces of the teeth.

Secondly, selecting an X-ray beam path which is tangential to the vertical axis of a tooth in the maxilla is unlikely to be suitable for a similar tooth in the mandible or even in the same jaw if interdental spaces exist and drifting has occurred. Similarly it has been shown, in Appendix IV, that an X-ray beam path which is ideal for revealing early approximal lesions on one tooth surface, may be incompatible with early diagnosis for a different surface.

Some image distortion is probably found in all intra-oral views and only becomes important if it masks early signs of disease or prevents accurate monitoring due to **variation** of the distortion.

Providing the principles of minimal but consistent distortion of images can be seen as compatible with the early diagnosis and accurate monitoring of disease, the task of designing a repositionable film holder becomes simpler.

Existing repositioning devices usually have rigid coupling between the X-ray collimator cylinder and the aiming device, a rigid backing to the film and some form of impression-based relocating method (Price 1975; Duinkerke et al 1977; Duckworth et al 1983; Pitts 1984b). This approach is unsuitable for general practice as it requires a large amount of chairside time and the more rigorous techniques are uncomfortable and unlikely to be tolerated by patients.

The reproducibility of existing repositioning devices is unknown since most studies have concentrated on the number and extent of approximal

surface overlapping (Moystad and Larheim 1989) rather than the magnitude of change between serial films.

Although simple repositionable film holders are not available for general practice, a number of commercial X-ray beam aiming devices exist. Rinn (Illinois, USA) manufacture a bitewing holder attached to an aiming ring. The holder is unstable in use as it often pivots on a mandibular canine leading to variable positioning between serial films. Flow X-ray Corporation (West Hempstead, USA) produce the Intrax film holder where the film is held loosely and can adopt different positions in use. Some holders have a flat biting platform in place of a paper tab which is stable in use, but has no reference method for serial repositioning (Kwik-Bite, Gentilino, Switzerland).

The purpose of this study was to design for general practice and longitudinal epidemiological studies a repositionable film holder which is simple and easy to use and does not require i) rigid coupling to an X-ray set, ii) an impression material to relocate the holder, iii) storage of individual holders for each patient and iv) a rigid backing to the film.

V.2 Materials and Methods

A bitewing holder was designed as a planar device which rests on the posterior occlusal surfaces of the teeth on both sides of the lower arch (marked as regions A and B, Figure V.1). This provided positional stability to overcome the tendency for a holder to pivot on a

mandibular canine, which was a potential problem identified from the Rinn holder.

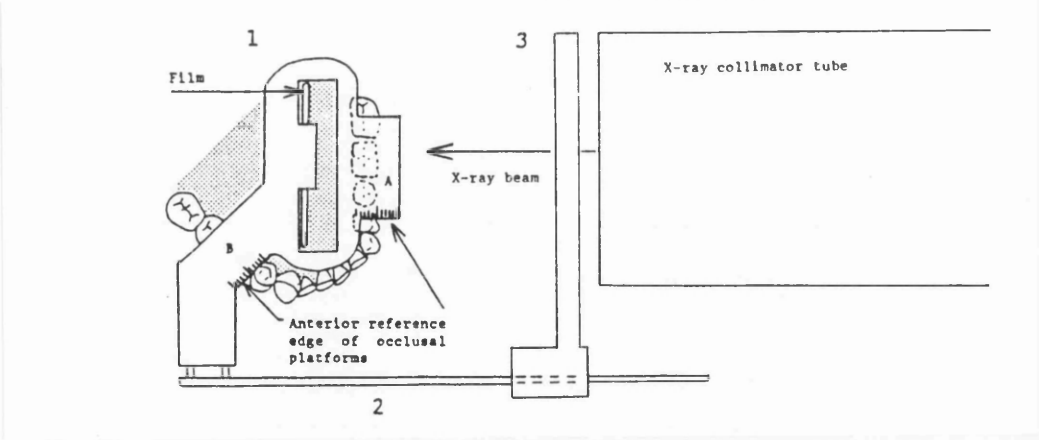


Figure V.1 Diagram of design for a repositionable bitewing holder. Key:- 1= Film holder, 2= Metal connecting rod, 3= Aiming ring.

A vertical bar extends 16 mm above and below the occlusal plane with retaining grooves to firmly hold a number 2 sized film in the horizontal bitewing position (Figure V.2).

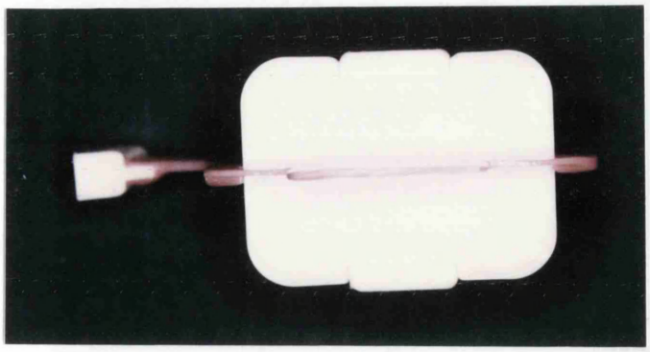


Figure V.2 Film firmly retained by grooved slots.

The holder is placed into the mouth so that the long axis of the film is parallel to the posterior line of the arch, with about 5 mm separating it from the lingual surfaces of the teeth. As the patient

closes together, the anterior reference edges of the occlusal platforms (Figure V.1) extend buccally beyond the upper arch allowing the position of the holder to be recorded relative to the teeth (Figure V.3).

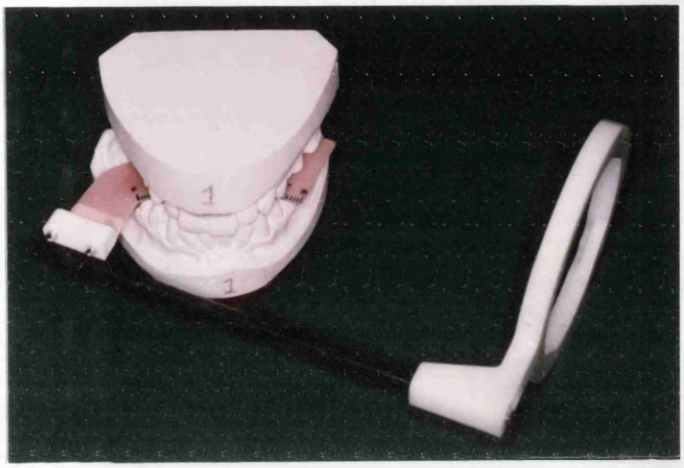


Figure V.3 Film holder reference edges extending beyond buccal surfaces when teeth in occlusion.

The position of the holder's left reference edge (Figure V.4 and marked A in Figure V.1) is recorded using the scoring method shown in Figure V.5.

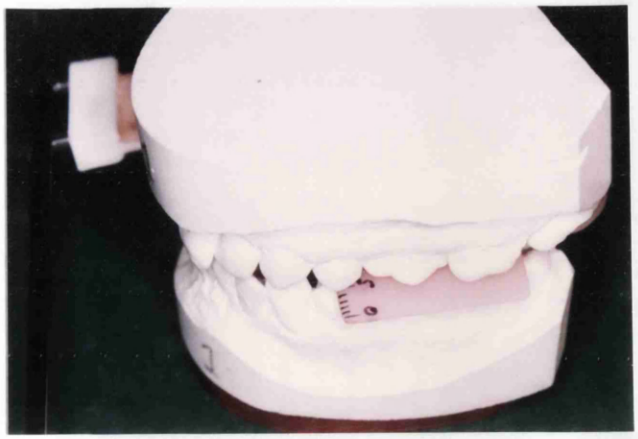


Figure V.4 Left reference edge of holder crossing cuspal tip of tooth 24.

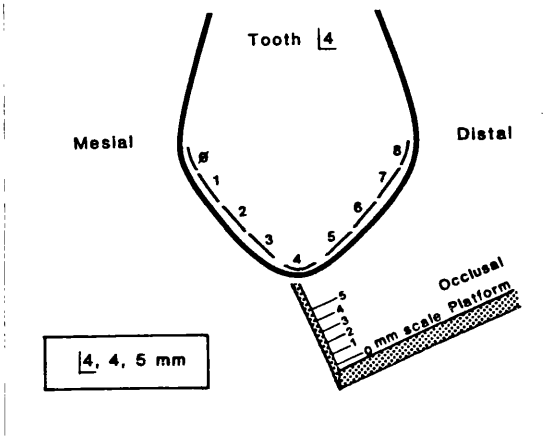


Figure V.5 Film holder positional scoring method. The cusp is divided into 9 regions and the portion crossed by the reference edge is recorded together with position on mm scale. In this example tooth 24, cusp portion 4 and 5mm would be recorded.

By eye the buccal surface of a cuspid tooth is divided into 9 regions. The mesial and distal marginal ridges are 0 and 8 respectively while the cuspal tip is 4. The intervening regions are divided into thirds and marked 1,2,3 and 5,6,7. The position of the holder is recorded by the region of the buccal cusp which would be cut by a perpendicular line from the anterior reference edge. In Figures V.4 and V.5 the reference edge is below the cuspal tip and would be scored as position 4. Additionally the position of the cuspal tip relative to a mm scale is recorded as 5 mm. A triplet of values indicating the recording tooth, anterior reference edge score and mm position for reference edge A would be recorded on the patient's record. Without moving the film holder the same procedure would be carried out on the other side for reference B. The left bitewing coordinates would be written on the patient's record as shown in Figure V.6. By rotating the film holder through 180 ^{o} the process can be repeated producing a second set of

film holder coordinates for a right bitewing (Figure V.6).

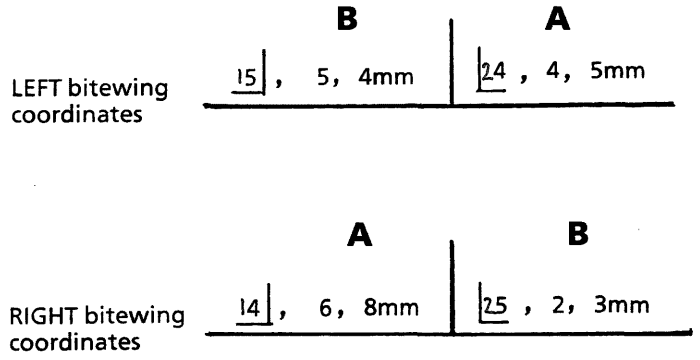


Figure V.6 Example of positional data for film holder in left and right sided bitewing projections.

The original film holder was developed using an acrylic prototype. However, this fractured easily and an autoclavable injection moulded polypropylene version was produced.

Connected to the film holder via a metal rod was a circular plastic ring to aid in aiming the X-ray beam. Positive docking of the ring to the X-ray head was investigated using rods projecting from the end of the collimator cylinder. However, the weight of the X-ray head made it difficult to avoid knocking the holder out of position. All attempts to link the X-ray head and the aiming ring were abandonned and instead the collimator cylinder brought to within 3 mm to 4 mm of the ring and lined up by eye.

7.3 Testing of the holder

The Royal Air Force have taken routine bitewing radiographs with the holder on 100 subjects with the intention of obtaining serial films 12 to 18 months later. Although the initial films have been exposed, administrative problems caused by the Ambulance Drivers' Strike and the Middle East Crisis have prevented a subsequent set of films from being made. Fortunately patient tolerance to the holder was recorded by 5 dentists on the 100 patients at the initial examination using a 1 to 5 scale (poor to good) with 3 being neutral.

Another study on 600 subjects is in progress by the Royal Navy but again the second set of films are not yet available.

A very limited study of 4 patients has been performed by Dr.K.Almas, Punjab Dental School, Pakistan. Using the repositionable holder, each patient had a horizontal number 2 sized bitewing radiograph exposed on each side of the mouth. With approval from the Local Ethical Committee in Lahore, the exposures were repeated 24 hours later after first positioning the holder according to the previously recorded coordinates.

The films were analysed using the digital stored regions of interest measuring system described in Chapter 5. Each bitewing was digitized to a pixel resolution of 0.05mm x 0.05 mm. The maximum overlap of the approximal surfaces in the horizontal and vertical direction was recorded for the adjacent surfaces of the second premolar and the

first molar in both jaws (Figure V.7).

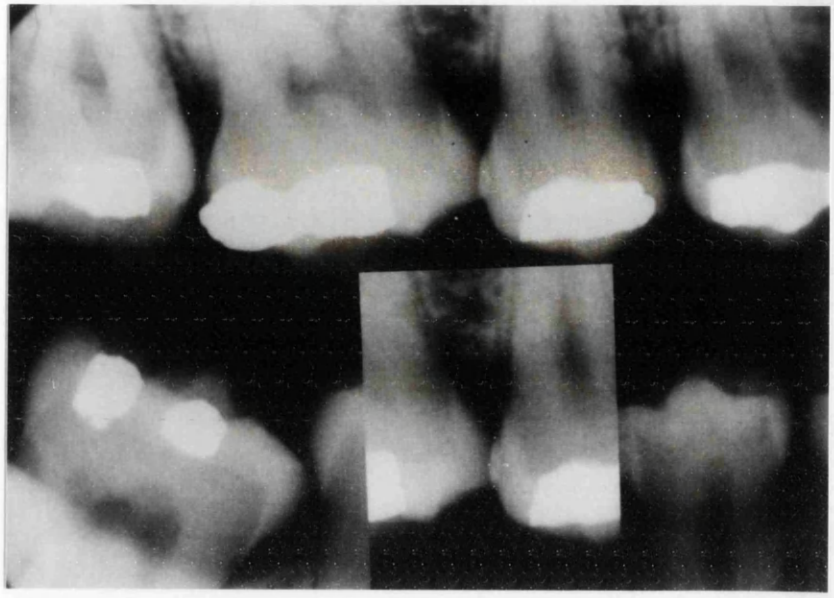


Figure V.7 Measurement of vertical and horizontal extent of approximal surface overlap, by region of interest method, to assess reproducibility of film positioning.

These regions were chosen since they correspond to the central vertical third of the film which was held rigidly by the holder and were therefore unlikely to be distorted from the palate or tongue. It was assumed that if the film holder and the X-ray collimator were correctly repositioned, very little change of the approximal surface overlap should occur and this would form the basis for proving reproducibility of positioning. The repositioning threshold was set at 0.15 mm since previous testing of the computer system has shown that this reliability can be achieved with a high confidence (Chapter 5). Any horizontal or vertical pair of overlap distances which changed more than this value between serial films and exceeded a 90%

confidence value, would be considered to be a failure to reposition the holder.

7.4 Results

Patients tolerated the film holder well with 88% (88 subjects) being either neutral or comfortable and only 12% being uncomfortable or very uncomfortable (Table V.1). Nine of the RAF subjects had the holder repositioned according to the stored coordinates and the average time required was 32 seconds.

Table V.1 Subject tolerance to repositionable film holder

Score	Number of subjects
1 Very uncomfortable	2
2 Uncomfortable	10
3 Neutral	36
4 Comfortable	46
5 Very comfortable	6
Total subjects	100

The reproducibility measurements showed that 6 out of 8 serial films had a horizontal overlap of one or both test sites maintained to a reliability of <= $\pm$ 0.15 mm change with a confidence of more than 90%. This was considered to be evidence of successful reproducibility. In the vertical direction 4 out of 8 serial films successfully maintained their measurements within the reproducibility threshold.

Table V.2 Change in approximal surface overlap between serial bitewing radiographs

		Horizontal		Vertical	
Film	Overlap site(FDI)	Change mm	M.Error mm	Change mm	M.Error mm
1L	25,26	0.30	0.05	0.04	0.05
	35,36	0.05	0.05	0.32	0.10
1R	15,16	0.08	0.15	0.12	0.16
	45,46	0.03	0.05	0.42	0.05
2L	25,26	0.12	0.00	0.66*	0.05
	35,36	0.05	0.10	0.16*	0.04
2R	15,16	0.24	0.02	0.41*	0.04
	45,46	0.16	0.05	0.70*	0.05
3L	25,26	0.69*	0.04	1.40*	0.10
	35,36	0.26*	0.00	0.21*	0.05
3R	15,16	3.23*	0.00	2.02*	0.47
	45,46	0.69*	0.00	2.05*	0.16
4L	25,26	0.00	0.00	0.02	0.05
	35,36	0.03	0.05	0.08	0.16
4R	15,16	0.00	0.00	0.42	0.00
	45,46	0.15	0.00	0.11	0.10

M.Error= measurement error; *= > 90% confidence geometry has changed (3.2 x error < change)

V.5 Discussion

One must be very cautious in interpreting pilot studies with limited test data. Nevertheless the horizontal reproducibility of positioning for 6 out of 8 films is very encouraging, especially as this includes the initial learning period by the dentist for the method. The reason for the lower reproducibility in the vertical direction is not immediately obvious and results from the larger studies will be needed to see if the errors vary with the plane of study.

A horizontal overlap of <= $\pm$ 0.15 mm is equivalent to an angular change of approximately <= $\pm$ 3-5 ^{o} (Sewerin 1981; McDonald 1984). The few experiments which have been performed use a single point of X-ray beam rotation and assume incorrectly that the shapes of the posterior teeth in the approximal region are regular curves. In reality it is probably a complex mathematical problem to accurately estimate the 3D X-ray beam changes responsible for any given alteration of the extent of approximal overlapping. However, it is probably safe to assume that variations <=$\pm$ 0.15 mm indicate a high degree of clinical irradiation geometry standardization.

A potential problem in using the film holder could be from parallax errors, due to variation of the operator's head relative to the patient, when determining the anterior reference edge tooth score. However, an experiment was devised to investigate the relationship between angular variation and change in holder position score. A film holder was rotated about a vertical pin in the central fissure of a

lower first molar in a plaster model. A 3 ^{o} rotation was measured from a horizontal protractor and the anterior reference edge B (Figure V.1) seen to vary by 1/3 of the mesio-distal width of a premolar on the opposite side of the arch (see Figures V.8, V.9). This change is equivalent to 3 units of the holder scoring scale. During the development of the method the author positioned the holder in the mouths of 70 patients. As a result of this it is felt that parallax reading errors would account for probably $\pm$ 1 score unit or approximately $\pm$ 1 ^{o} of X-ray beam change.

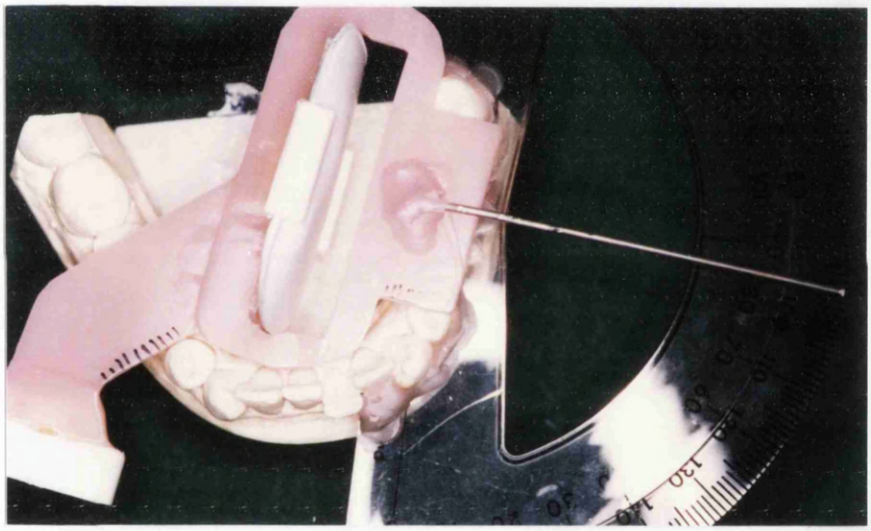


Figure V.8 The effect of small horizontal angular variation of holder position on buccal tooth scores. Holder anterior reference edge B would be scored as 8 for tooth 44.

In most subjects, the film was placed about 5mm away from the palatal sufaces of the teeth, in order to prevent discomfort against the palate. Compared to flexible film holders, such as paper tabs where the film is close to the teeth, the images from the repositionable holder will be magnified slightly more. However, providing the

positioning is consistent, the magnification should not vary between serial films affecting the validity of comparing the images for change.

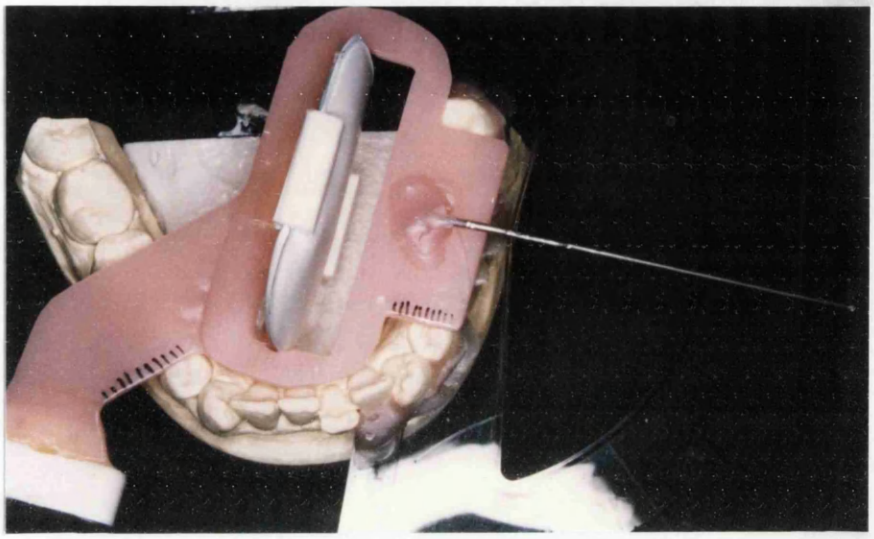


Figure V.9 A 3 ^{o} change in horizontal position of holder alters buccal reference score by 3 units to 5.

V.6 Conclusions

In conclusion a repositionable film holder which is simple and quick to position has been designed and tested on a limited number of patients. The reproducibility was high in the horizontal direction but lower in the vertical plane. A larger survey is required to confirm these findings. The holder was well tolerated by a group of 100 adult subjects. Comparisons with other holders are planned. If general practitioners wish to standardize irradiation geometry, then the repositionable bitewing holder may offer a way of achieving this goal.

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