Chapter 1

INTRODUCTION

PROBLEM STATEMENT

The estimation of age at time of death is an important step in the identification of human remains. If this age can be accurately estimated it will significantly narrow the field of possible identities that will have to be compared to the remains in order to establish a positive identification. To achieve this there are many methods available to the forensic dentist, anthropologist or pathologist. Some of the more accurate methods of age estimation, in the juvenile and younger adult, have been based on the assessment of the degree of dental development as it relates to chronological age. These methods rely on radiographic assessment of the degree of calcification of the forming dentition. This assessment is then compared to tables or diagrams of examples of known age to estimate the chronological age of the individual.

The problem faced at the New South Wales Department of Forensic Medicine (NSWDOFM) is that few, if any, of these dental methods can be used to reliably predict age at time of death of unknown remains.

One such method trialed at the NSWDOFM is that of Canadian researcher, Demirjian (Demirjian et al., 1973), who developed a system that estimates chronological age from dental development. It was reported that this method gave a valid estimate only when applied to French-Canadian children, being the population on which the system is based. When used on local cases at the NSWDOFM significant errors in age estimates have occurred. The problem faced by NSWDOFM is not unique to this location. Studies conducted by other researchers have attempted to apply the Demirjian system to different populations but have found that (although it discriminated well between cases of similar age) it did not accurately predict chronological age across the samples.

RESEARCH QUESTION

To determine whether or not the Demirjian system for estimating chronological age of human remains could be improved upon.

PURPOSE OF THIS STUDY

Given that maturity is a function of age, the aim of this treatise is to explore the utility of estimating chronological age from dental maturity data for use in forensic odontology, where dental maturity data is derived according to various systems.

In particular, the objectives of the study were:

1. To test the applicability of the Demirjian system and standards to a Sydney sample population;
2. To develop age prediction models, using the defined stages of the Demirjian system, and based on a subset of a large sample of Sydney children;

3. To test the age prediction models as described in 2 above on the remainder of the sample, to determine whether age estimates based on the Demirjian system are the same as that based on modifications of the system, or other systems, and to determine the best model for use in the prediction of age in this portion of sample; and
4. To recalculate the chosen regression models using the entire sample.

RESEARCH APPROACH

To achieve these objectives, this treatise will first examine the background of forensic identification in general in Chapters 2 through 4. Chapter 2 will give a brief overview of the history and scope of forensic dentistry; Chapter 3 will look at the reasons why there is a need to identify human remains; and Chapter 4 examines the various methods of forensic identification that are available. This review will include examination of the techniques available, the information that can be gained from these investigations, and the conclusions that can be drawn from this information. In Chapter 5 the various methods of estimation of age at time of death are reviewed. This includes the most common dental and osteological methods of ageing. Chapter 6 examines the chronology of tooth development, the factors that affect dental development and specifically reviews the different systems of estimating age at time of death from the degree of dental development. It is in this Chapter that the original work of Demirjian (Demirjian et al., 1973), is explained and analysed in detail.

Chapter 7 describes in detail the materials and methods used in this Sydney study to collect, process, and analyse the data. Orthopantomagrams (OPGs) of 3261 children were examined and analysed according to the Demirjian system. Age predictions were made using (1) the published standards of the Demirjian system, (2) standards developed in this Sydney study using a proportion of the sample, and (3) also using those of Schour and Massler (Schour and Massler, 1941). The accuracy of the predictions of these systems was analysed and compared. A final model was developed using the whole sample and prediction curves were produced. Inter- and intra-observer error was measured to assess the degree of agreement between observations and analysed using the kappa statistic.

Chapter 8 contains the results of the research. Chapter 9 contains a discussion of these results, the conclusions, and recommendations for further research in this area.

Chapter 2

THE HISTORY AND SCOPE OF FORENSIC DENTISTRY

2.1 HISTORY

The identification of human remains through recognition of specific characteristics of the dentition is a method that may have been used for thousands of years (Luntz, 1977). The first recorded case, however, dates from the middle of the 1st Century AD (Cary, 1925). There then appeared to be a growing interest in the latter half of the 19th Century in the United States, as indicated by the number of forensic articles in the dental journals of the time (Luntz, 1977). It was not until the 1960s that a resurgence in interest in the field prompted the United States Armed Forces Institute of Pathologists to offer a course in the field of forensic dentistry. That course still runs today as do many others at dental schools the world over.

The methods used today are far more developed but the same basic principles that were used in the past still apply. By way of illustrating this point, what follows are some noteworthy cases involving dental means of identification.

In 49 AD Agrippina, the mother of a 12 year-old boy named Nero, married Claudius the Emperor of Rome at the time. It was shortly after she married Claudius that Agrippina ordered the murder of Lollia Paulina. Lollia Paulina was a rich divorcee whom Agrippina perceived as a threat to her own marriage. As proof that the deed was done she ordered her soldiers to return with the head of their victim. It has been reported by Dio Cassius in his history of Rome, that on presentation of the severed head Agrippina stared into the distorted face but unsure as to the identity of the head, parted its lips and looked at it's distinctive dentition. Only then was she satisfied that they had killed the right person (Cary, 1925).

In the late 18th Century one of the first recorded cases occurred whereby a dentist provided a post-mortem identification of one of his patients from his dental work. Paul Revere, most well known for his part in the American Revolution, was a silversmith and engraver by trade. He practiced as a dentist from 1768 to 1788, using skills taught to him by John Baker, a surgeon-dentist from England. In 1775 Revere constructed a fixed silver wire bridge for his friend Dr Joseph Warren. Warren, with the commissioned rank of Major General, was later killed at the Battle of Bunker Hill and buried in a mass grave at the site. The English left the area about a year later and it was at this time that Revere, Warren's brothers and a few friends went to recover the remains of Dr Warren. The extent of decomposition of the remains was such that the only way they could positively identify them was by Revere's recognition of the bridge he had constructed a year or two before. Major General Warren was then reburied at Kings Chapel in Boston (Ring, 1976).

It then was not until the mid-19th Century that forensic dentistry began to attract a growing interest. Many cases appeared in dental journals of the time (Luntz, 1977). In 1846 the skeletal remains of a body recovered from a crypt near a church in Paris were positively excluded as being those of Louis XVII on the basis of the level of development and condition of the teeth (Hill et al., 1984).

In 1850 dental evidence was first admitted into a trial in the United States when a dentist, Dr Nathan Keep, presented ante-mortem casts of his patient Dr G. Parkman and successfully fitted the remains of a lower denture to them. The denture pieces had been recovered, along with the charred remains of his former patient, from a furnace at the Massachusetts Medical College of Harvard University. Further detail of ante-mortem adjustments made to the denture by the dentist in the presence of his assistant was also visible. The evidence was accepted as positive identification that the remains were indeed that of Dr Parkman (Campbell, 1958).

In 1869, two female bodies recovered after a boat fire on the Ohio River were misidentified as each other. The family of one of the victims suspected this and called upon the family dentists of both victims to resolve the issue. Both dentists examined one of the bodies and quickly came to the conclusion by a process of exclusion that the initial identifications were incorrect and had to be reversed (M'Grath, 1869).

In 1873 in Baltimore, a case of insurance fraud was uncovered when a dental post-mortem examination of a body recovered following a house fire revealed a dentition blatantly inconsistent with that of the alleged (and recently heavily insured) victim as reported by the victim's wife. Unfortunately for the insurance company they failed to prove the victim was still alive, the dental evidence not swaying the court, and the widow was awarded the payout. About seventeen months later the husband of the 'widow', who had still been alive up until that point, was murdered by his brother-in-law. One can assume from this case, that although not accepted by the court at the time, the dental evidence was correct (Grady, 1884).

In 1882, a dentist in Southampton positively identified a skull presented for his examination as that of one of his patients, Mr Henry Powell. The dentist had retained a wax pattern impression he had taken of the deceased some months earlier in the construction of some gold restorations. This impression fitted the dentition of the skull perfectly, confirming the identity of the deceased (Hill et al., 1984).

In Neuilly in 1890 impressions were taken, and models constructed of the teeth of a strangulation victim. The reason behind this step was that during the course of the investigation the police were made aware that at about the time of the murder a young man had approached a nearby pharmacy to have a wound on his hand dressed. Within one week, a suspect was apprehended and the models of the victim's irregular dentition matched perfectly to the bite mark on the suspect's hand. The suspect was convicted of the murder (Hill et al., 1984).

A little over one hundred years after Paul Revere identified the remains of his friend Dr Warren, a fire raged through a bazaar in Paris. It was 1897 and the fire that swept through the Bazar de la Charité lasted only 10 minutes but claimed 126 lives. After all but 30 of the victims were identified through their clothing and personal effects, it was the Paraguayan Consul who suggested that the dentists of the missing persons come to aid in the identification process. A professor at the dental school in Paris at the time, Dr Oscar Amoëdo, wrote a paper on the dentists' role in the disaster (Amoëdo, 1898b), and later went on to write a book titled L'Art Dentaire en Médecine Légale (Amoëdo, 1898a). The book was over 600 pages in length and covered many aspects of forensic dentistry including dental identification, bite marks, traumatic lesions, and dental jurisprudence. It was his work in this area that has prompted some authors to name him the 'father of forensic odontology' (Luntz, 1977). Interestingly enough it was in his journal article on the disaster at the Bazaar that he noted the need for an internationally consistent standard of dental charting. This one problem still plagues forensic dentists today.

2.2 THE SCOPE OF FORENSIC DENTISTRY TODAY

The history of forensic dentistry is full of both individual cases of identification as well as those of the mass disaster. While these areas are still the main focus today the scope of modern forensic dentistry has grown well beyond this.

Sopher defined four main areas of application (Sopher, 1976):

i) identification of human remains by dental methods,

ii) bite mark comparison as an identification and detection method,

iii) medico-legal assessment of trauma to the oral tissues, and

iv) dental malpractice and negligence.

2.2.1 Identification of Human Remains

In cases where individual remains cannot be visually identified other means must be employed. These cases include severe decomposition, mutilation, incineration, or immersion and the associated emollition of the remains and can occur in many scenarios. It is not only in mass disasters and wartime that these occur - isolated incidents in peacetime are very common.

The human dentition can provide much information about the identity of an individual owing to its unique properties. Of all the hard tissues in the human body the teeth have the least amount of biological turnover. Thus, in the absence of disease, teeth will remain remarkably stable in form throughout life. The teeth are also in the useful position of being among the most indestructible of the hard tissues of the body both in life and after death, often despite decomposition or emollition of the remains or even despite the ravages of time (thousands of years in many cases). However our teeth are often changed either structurally or chemically by a disease process or by our treatment of that process. It is the recording of the natural state of the dentition, the disease processes present, and the treatment provided by dentists that is detailed in ante-mortem dental records. These records exist in many forms, including written narrative, charting, radiographic records and photographs.

It is the comparison of the ante-mortem records to those obtained from the remains post-mortem that allows for an identification of the individual concerned. This method is expedient, accurate and cost effective, but relies entirely on the provision of some form of ante-mortem record. A number of circumstances occur where these records are not available, such as: if the dentist of the suspected deceased is unknown; if the deceased received dental treatment infrequently from varied unknown dentists; or, if the deceased received no dental treatment at all. In such cases an indication as to the possible identity of the deceased may still be gained by dental means. Indicators of race, sex, age, lifestyle/occupational markers, and more broadly, species can all be obtained with varying degrees of accuracy from the dentition.

Other means of identification do exist and are often used either in conjunction with or instead of dental means. Clothing, jewellery and other personal effects can give an indication as to the identity of an individual. Medical records and other radiographs can also prove extremely useful in revealing the existence of previous hard tissue injury, screws, plates and other methods of orthopaedic fixation, prosthetic replacement of joints and blood vessels.

In Australia today dental evidence, fingerprint evidence and DNA analysis are the only methods of identification that can each stand alone to positively identify an individual without corroborating evidence. However, unlike the United States, in Australia very few people, other than convicted criminals have their fingerprints recorded, thus providing a limited application of this method of identification. Further, in cases of severe burning, decomposition or emollition it may be impossible to obtain fingerprints from the remains due to the extensive changes in soft tissue, whereas the dentition may still be intact. It is this durability of the dentition that often allows for a positive identification where no other means may effectively do so. DNA analysis can also be used to identify an individual but due to the high cost and time involved, it is not often used as the first choice.

2.2.2 Bite Mark Comparison

The indentations or marks left on human tissue and other objects by human teeth can often be used to identify a suspect. The force required to penetrate skin with the teeth is of a magnitude that generally indicates the act was of an aggressive nature. As such, the method of a comparison between the bite marks left on a victim and the dentition of a suspect has application in homicide, assault and child abuse cases. Although penetration of the skin does not always occur in bite mark cases, the force placed on the tissues by the teeth is often enough to leave marks that can be analysed. In other cases objects such as apples, gum, cheese, chocolate and tape (used to restrain a victim) have been found at the crime scene with teeth marks in them (Whittaker and MacDonald, 1989). The comparison of these marks to the dentition of a suspect may confirm their presence at the crime scene but would not necessarily incriminate them. Regardless of the nature of the case the techniques involve careful comparison of the marks and the dentition, paying particular attention to arch form, tooth size, tooth morphology, rotation, inclination, the presence of supernumerary teeth or absence of one or more teeth, any indications of previous dental treatment or anomalies.

As is sometimes the case, doubt may arise over whether or not the injury is actually a bite mark. Keiser-Nielsen and Jakobsen have suggested guidelines for the detection and analysis of bite marks in human tissue (Jakobsen and Keiser-Nielsen, 1981; Keiser-Nielsen, 1970). These state that for an abrasion on the skin to be positively identified as a bite mark a minimum of the imprint of 4 to 5 teeth from each arch would need to be present. The American Board of Forensic Odontology uses a broader definition, providing three zones of confidence in the diagnosis of a bite mark:

i) Possible Bite mark: An injury showing a pattern that may or may not be caused by teeth; could be caused by other factors but biting cannot be ruled out. The general shape and size are present but distinctive features such as tooth marks are missing, incomplete or distorted or a few marks resembling tooth marks are present but the arch configuration is missing.

ii) Probable Bite mark: The pattern strongly suggests or supports origin from the teeth but could conceivably be caused by something else. The patterns show basic/some characteristics of teeth arranged around arches.

iii) Definite Bite mark: There is no reasonable doubt that teeth created the pattern; other possibilities were considered and excluded. The pattern conclusively illustrates classic features of dental arches and human teeth in proper arrangement so that it is recognisable as an impression of the human dentition (American Board of Forensic Odontology, 1997).

Another area of bite mark analysis is its application to non-human bites. The use of these techniques in assessing animal attacks may help identify the animal responsible. It is also useful in ruling out scavenger activity when examining markings on skeletonised remains.

2.2.3 Interpretation of Oral Injury

An important area of forensic dentistry is in the interpretation of oral injury. This area includes examination of injury to the intra-oral soft tissues, tongue, teeth and bony structure of the jaws as well as to the circum-oral soft tissues. This examination may be for cases involved in either civil or criminal legal proceedings. It may require an understanding of the force required to cause specific damage to the oral structures. It may also require a knowledge of poisons, drugs and other caustic agents and their effects on soft tissues, as well as the effect of the forced entry of these substances to the oropharynx and gastro-intestinal tract (O'Reilly, 1986). An example of this could be found in the burns that may be caused in the mouth, oropharynx, and lips by the administration of a corrosive poison.

2.2.4 Malpractice and Negligence

The final main area of forensic dentistry is that of malpractice. Malpractice or professional misconduct is a term that covers a wide range of actions. It can be defined as an act or continuing conduct of a professional that does not meet the standard of competence of that profession. The Dental Practice Act of NSW provides the following definition of professional misconduct, 'in relation to a registered dental care provider, means unsatisfactory professional conduct of a sufficiently serious nature to justify suspension or cancellation of the dental care provider's registration' (Dental Practice Act (NSW), 2001). Should the alleged malpractice result in professional or legal proceedings an expert witness, a specialist in the field of treatment in question, is usually called upon for an opinion.

Professional misconduct, while often associated with negligence, is not strictly limited to it. Professional misconduct can include any such behaviour as to warrant suspension such as contravention of other aspects of the Act. Such behaviour may include, but is not limited to failure to comply with registration requirements, conviction of a sex offence or violent crime, fraud, and of course negligence. Fraud is generally defined as 'obtaining material advantage by unfair or wrongful means' (Rutherford and Bone, 1993). In the dental setting, fraud may take many forms but the more common examples involve overcharging, or overtreating of patients, or submission of false health insurance claims. When such cases are investigated, it will usually involve examination of treatment records (including written documents, radiographs, casts) and comparison to the actual treatment provided to the patient in question in order to ascertain the validity of the documented, and/or claimed, treatment. It is assisting in this review process that dentists perform a forensic role.

Negligence can be defined as 'the failure to exercise care towards others which a reasonable or prudent person would do in the circumstances, or taking action that a reasonable person would not' (Hill and Hill, 2004). In the dental setting, the ‘reasonable person’ is often a dental specialist, and will be the one to attest to what is an acceptable standard of care given the level of training of the practitioner. For an act to be considered negligent, the court needs to find that:

a) the accused had a duty of care to the injured party;

b) the action (or failure to act) was negligent, ie. did not meet the acceptable standard (as set by an expert witness);

c) that the negligent act was the proximal (or immediate) cause of the injury; and

d) that the resultant injury was ‘reasonably foreseeable.’

In order to determine whether or not treatment was provided to the appropriate standard of care the expert witness; the dentist, may be called upon to review the case. In doing so the dentist may be required to review records such as radiographs, casts, statements, and written reports, examine patients and provide expert testimony on the type and standard of treatment provided. The expert may also be required to review the accuracy or otherwise of any diagnoses made. Further testimony may be required of the expert witness to attest as to whether the treatment provided was the proximal cause of the injury and whether such an injury would have been reasonably foreseeable in the circumstances. It is through this process that the dentist makes a forensic contribution to the review of the case.

It is important to note that across the scope of forensic dentistry these areas of expertise are not necessarily limited to the realm of the forensic odontologist. Indeed, it is not uncommon, especially in rural areas, for the general dental practitioner to be called upon to undertake any and all of these tasks. Further, in cases of malpractice the expert is usually a specialist in the field of treatment provided.

While the role of the forensic odontologist is quite diverse, it is the identification of the deceased that is the mainstay of the profession. The reason why the area of identification is so prominent in the casework of the forensic odontologist has its roots in the primary need for identification of the deceased. The next section will examine the reasons why this need for identification exists.

Chapter 3

THE NEED FOR IDENTIFICATION OF HUMAN REMAINS

Forensic Dentistry can certainly provide an accurate method of identification but it is the initial requirement for that identification that will be examined in this chapter. The justification for identifying human remains is a multifaceted one that encompasses religious, moral and social, investigative or technical and legal fields.

3.1 SOCIAL AND RELIGIOUS REQUIREMENTS

The United Nations Universal Declaration of Human Rights (UDHR) states that every child immediately after birth shall be given a name, and hence an identity. It also states that everyone has a right to recognition as a person before the law (United Nations, 1948). While after death a body is not recognised as an individual before the law, the unique identity that the individual held while still living is required to be confirmed at death so the rights and obligations of the survivors of the deceased can too be protected. As a signatory to the UDHR, the Australian Government and the society that it represents have an obligation to recognise an individual both in life and in death. Without identification of the deceased, this cannot be achieved.

For the family and friends of the deceased, identification is seen as paramount. It allows the family an opportunity to grieve without the doubt that occurs when the deceased is not positively identified. Any doubt as to the identity and hence fate of an individual can result in great distress and grieving on the part of the family and friends that may continue for many years. Positive identification, although emotionally distressing for the family, does allow a finality that would otherwise elude them.

Today in Australia, but more so in the United States, the Government places considerable effort in recovering the remains of those who were killed in wartime. These remains, often recently discovered in overgrown air crash sites, are often identified by dental means. This effort to identify and recover the bodies of those men and women who died in the service of their country is made out of a moral obligation to the families of the deceased. It is an obligation to put an end to the doubt and the grieving that these families have endured for decades.

The human corpse is more than a utilitarian object, it has sacred meaning. Every religious faith has beliefs pertaining to the treatment of corpses and there are laws that govern the treatment and the burial of the dead. While these laws have recognised the corpse's instrumental value as an object for scientific study, clinical teaching and commercial gain, they have accommodated the desire to respect remains (Nelkin and Andrews, 1998). Laws in every state and territory in Australia express our cultural concerns over proper treatment of remains. Different religions have different beliefs and customs regarding the treatment of the dead but most have a common basis in putting an individual to rest at the end of their life. The exact intention of the ceremonies that surround this process will not be expanded upon here. It is important, however, to recognise that the differences between the customs of the various religions are significant. As such, it is crucial that upon the death of an individual their identity be confirmed in order for the appropriate customs and rituals to be observed. When the religious and personal interests of the deceased are not respected family members may suffer levels of emotional distress. In 1984, a US Court awarded damages for mental suffering to two families when, as a result of a mix-up between two bodies, the undertakers erroneously prepared one body for an Orthodox Jewish burial while the other was embalmed and prepared cosmetically for a Roman Catholic burial. A judgement in a similar case stated, '… where they believe that the treatment will affect the afterlife of the deceased, the impact [of distress on the next of kin] is inevitably greater' (*Kohn v. United States*, 1984).

In those cases where the identity of the individual or group of individuals is not known, as happens so often in wartime, a compromise is often reached. A memorial such as the Tomb of the Unknown Soldier in the Australian War Memorial in Canberra, ACT, exists partly to meet these social and religious requirements, providing an icon that represents all those who remain unidentified.

3.2 FINANCIAL AND BUSINESS REQUIREMENTS

Although based in law, these requirements may be considered separately as they apply to the relationship between the deceased and institutions other than the State. This area includes such considerations as life insurance payouts, outstanding debts and other liabilities. Although the latter two are covered under the laws of succession and will be addressed in the section on legal aspects, the first area is worth mentioning. An insurance company will not make payment of a claim unless positive identification of the deceased is made. The exception to this is in the case where the body is not recovered; a period of seven years unheard from is required for a Coroner to pronounce them dead (Stone, 1981), following which the insurance company is obliged to honour the claim. Another example occurs where an accident is caused by a client of an insurance company and as a result of that accident the client is not visually identifiable. The company will not admit liability until the positive identification of the policy holder can be established.

3.3 INVESTIGATIVE REQUIREMENTS

The identification of bodies in accidents involving multiple fatalities such as aircraft, bus or car accidents can prove valuable in the ensuing investigations. By comparing the pre- and post-crash positions of the individuals involved, much information can be gained about the events that occurred before, during and after the incident. Obviously, the identity of the individuals must be established for this to occur. This information can be of use in the assessment of not only the cause of death of the individuals but also to the mechanism or process of the accident.

3.4 LEGAL REQUIREMENTS

Finally, but no less importantly, is the area of legal requirements surrounding the identification of human remains. The New South Wales Coroners Act 1980 gives the reasons for which an inquest must be held. There are many reasons for a death to become a Coroner's Case, the most common of which are 'suspicious or sudden deaths', but the full list can be found in section 13 subsection 3 of the Act:

(a) the person died a violent or unnatural death,

(b) the person died a sudden death the cause of which is unknown,

(c) the person died under suspicious or unusual circumstances,

(d) a medical practitioner has not given a certificate as to the cause of death,

(e) the person was not attended by a medical practitioner within the period of 3 months immediately preceding his or her death or suspected death,

(f) the person died while under, or as a result of, or within 24 hours after the administration of, an anaesthetic administered in the course of a medical, surgical or dental operation or procedure or an operation or procedure of a like nature, other than a local anaesthetic administered solely for the purpose of facilitating a procedure for resuscitation from apparent or impending death,

(g) the person died within a year and a day after the date of any accident to which the cause of his or her death or suspected death is or may be attributable,

(h) the person died while in or temporarily absent from a hospital within the meaning of the *Mental Health Act 1990* and while the person was a resident at the hospital for the purpose of receiving care, treatment or assistance (Coroners Act (NSW), 1980a).

One final reason for the conduct of post-mortem examination is given in Section 14 subsection 3 of the Act, which states that 'a post-mortem examination may be undertaken to determine if an inquest is to be held' (Coroners Act (NSW), 1980b).

In conducting an inquest it is the duty of the Coroner under section 22 of the Act to determine

'whether a person died and, if so:-

a) his identity

b) date and place of his death

c) manner and cause of death' (Coroners Act (NSW), 1980c).

It is part (a) of this section of the Act that provides the legal requirement to positively identify the deceased. It is in the pursuit of these findings that the Coroner may employ medical and other scientific experts as required. The forensic odontologist is often the scientific expert utilised to establish the identity of the deceased if no visual identification can be made. It is not until the Coroner is satisfied that the requirements of the Act have been met, which obviously includes a positive identification of the remains, that the body can be released to the family of the deceased for burial or cremation.

In the context of criminal law, identification plays an important role. Identification, often by visual means, is frequently one of the first steps leading to the prosecution of an offender in many criminal cases. So too is the identification of offenders by DNA and fingerprint techniques. Bite mark analysis has been used to identify assailants involved in assault cases where they have bitten their victims. Post-mortem identification of a victim is important where an individual stands accused of murder or manslaughter – if the victim cannot be correctly identified the case may not proceed. It should be noted, however, that a body does not necessarily have to be found and identified for a conviction of murder to be made but that in such a case there will be a far heavier reliance on circumstantial evidence by the prosecution.

Most actions in tort continue after the death of the complainant with the exception of those of a dignitary nature such as defamation (Clement and Ranson, 1998). In such cases it is important for the discontinuation of an action or action upon the death of the tortfeasor that they are correctly identified. Where the action is brought about by a dependant of the deceased in the case of death caused by a wrongful act or negligence, it is also necessary that the identity of the deceased be confirmed for the action to proceed.

Contracts may remain extant beyond the death of one of the parties except in circumstances where the requirements of the contract are personal to the deceased and as such prevent the terms of the contract being able to be met post-mortem. Again, in such cases it is necessary that the identity of the deceased be confirmed for the contract to be terminated (Clement and Ranson, 1998).

There are other legal proceedings that cannot be undertaken until the deceased is positively identified. Most notable of these is the enactment of a legal will. Proof of death, of which the identification of the deceased is integral, is a prerequisite for granting probate. Again, as previously mentioned the exception to this rule is the presumption of death that can be made by a Coroner if no evidence is found that indicates that the individual has been alive for the previous seven years assuming all the appropriate enquiries have been made (Stone, 1981).

From this brief overview, it can be seen that identification of the deceased is not only a right but also a social and legal responsibility. The method of this identification may be by one or more of the many techniques available today. The next chapter will examine a range of these techniques.

Chapter 4

METHODS OF IDENTIFICATION

The importance of the positive and timely identification of the deceased has been established in the previous chapter. It is the methods by which this may be achieved that we will now focus on. These techniques are many and varied as are the circumstances under which they are used. Different countries, regions, and even individual investigators have their own preferred techniques which may further differ depending on the case at hand. Sassouni suggested that the mode of human identification takes one of two forms, either reconstructive or comparative, depending on the presence or absence of a suspected identity of the victim and hence the availability of ante-mortem records (Sassouni, 1963). This distinction can be applied to all of the identification methods available to the investigator today. The methods available are universal in their application, limited only by the available data, resources and expertise. These methods can be divided into six main categories; visual, property, medical, fingerprints, DNA and dental.

4.1 VISUAL

The most basic and widely used form of identification is based on visual recognition of the face. From a very early age, humans develop the ability to recognise the faces of their parents – the ones who will nurture them and help them to survive. It is a skill humans use every day and one that is heavily relied upon in the forensic context. When a body is to be identified visually, it is usually the case that the identity of that body is already assumed by virtue of the surroundings and circumstances of the death. The process of visual identification in these cases is a confirmatory one and is usually undertaken by a relative or close acquaintance of the deceased.

In a minority of cases, visual identification of the deceased is not possible due to burns, trauma, tissue loss and degradation that renders the face of the deceased unrecognisable. While these factors will prevent the possibility of a visual identification being made, there are other, more subtle reasons why visual identification may not be successful. These include such factors as; loss of facial muscle tone in the body rendering the face unrecognisable; the mental trauma of seeing a dead body; the stress of making the identification while coping with the grieving process; the pallor of death; the lack of expression and unkempt hair; the lack of make-up and, dentures all may put doubt in the mind of the person asked to make the identification (Clement and Ranson, 1998). Finally, post-mortem loss of blood and interstitial fluid from the tissues of the face occurs as it drains away under the force of gravity. This tends to give the face a slightly sunken look that can significantly change its appearance.

Unfortunately, in many developing countries, visual identification is often the only method of identification available regardless of the condition of the remains. Especially so in cases of mass disasters, the bodies of the victims or photographs of their faces are lined up for the family members to walk past and pick out for a ‘positive identification.’ For these reasons, while visual recognition is often not the most reliable method of identification it is certainly the most cost effective and most common.

4.2 PROPERTY

Physical items found on or near a body can be used to aid in the process of identification. Items such as jewellery, wallets/purses, watches, and rings may have unique attributes that help identify the person to which they belong. It is important to note that as items of property are often easily transferable between people, their use in identifying an individual is limited to that of a corroborative nature. While they may lend support to a positive identification made by other, more substantial means, it is unlikely that an identification would be made on property evidence alone.

4.3 MEDICAL RECORDS & ANTHROPOLOGICAL METHODS

Medical records can provide a history of medical treatment that may have left behind physical vestiges that can be used to assist in the identification of an individual. These records may be in any form, for example, written surgical notes, lab results, radiographs and other forms of imaging such as magnetic resonance images (MRIs). The treatment detailed by such records may include surgery that has left scars, placement of orthopaedic plates and wires, and prosthetic implants including venous grafts. They may also record pathologies such as fractures, bony lesions, and other physical abnormalities that may be used to aid in identification. The majority of this type of information is usually of a corroborative nature, with the exception being prosthetic implants such as pacemakers that have unique serial identifiers.

Non-metric observations and anthropometric measurements of the body and limbs, in part or in whole, can provide valuable information in the identification process. As any set of measurements or observations may not be unique to one particular individual their use is reconstructive and not normally comparative. They can help provide race, sex, age and height estimations for a body when this information is otherwise unknown. They can also be used to calculate an estimate of height when only partial remains are recovered (Krogman and Iscan, 1986). The measurements are made and compared with known standards, or placed in regression formulae, to calculate age and height ranges with associated confidence intervals. This information can then be used to narrow the search of, say, a missing persons database.

4.4 FINGERPRINTS

Since the late 1920s fingerprints have been seen as an accurate and therefore very useful means of identification. The individual properties of every fingerprint confer a uniqueness that, like DNA and dental identification, provides enough information to positively identify an individual without the need for corroborating evidence. The principle behind the techniques in this area is that of comparison of a facsimile of the pattern of fine ridges on the skin of the fingertip of an individual with another recorded facsimile. It is the investigators' task to discover any areas within the two prints that are identical. These are referred to as points of concordance. The more points of concordance that are found, the more reliable the identification will be. It is an identification based on the probability of someone else having the same combination and arrangement of ridge patterns. So as the number of distinct points of concordance increases, the probability of finding another print the same decreases. The Courts have accepted the proposition that there comes a point where the number of concordant points give a very high probability that the print is unique and that the identification can be made 'beyond reasonable doubt' (Block, 1969). The number of points required for this decision varies from country to country. It is the position of the International Association for Identification that, rather than a set number of points of concordance, it is up to the fingerprint expert to offer an opinion, based on their training and experience and a thorough examination of the prints in question as to whether the prints are a match. This position is one that is also held by Police and the Court system here in Australia today (CrimTrac, 2004).

The ridges, or friction ridges as they are more correctly known, are small elongated elevations in the skin that run more or less parallel to each other. Along each ridge top is a row of pores, however these are too small to be seen with conventional printing techniques. It is the large number of ridges positioned with a high degree of randomness that confers the uniqueness of the fingerprint. Other areas of the body have unique ridge patterns too. They include the palms of the hands, soles of the feet and the lips.

The patterns formed by the randomly developed friction ridges are identifiable and as such have been classified by their individual pattern. It is the description of the combination of these patterns that is used to describe a fingerprint. Over 50 different methods and modifications of methods exist in fingerprint analysis today (Zonderman, 1999). Two of the main divisions in these systems are that of the Ten Print Systems and that of the Single Print Classification Systems. The Ten Print systems are based on the recognition of such features as the loop, arch and whorl as well as scars, folds and other irregularities. They also examine secondary features such as the slope of the ridges and the distances between the left or right deltas and the core (measured in number of ridges). The Single Print systems use the same or similar features as the Ten Finger systems but as there will be fewer features to compare, more detail is needed. The Battley system is one such example where the single print is overlayed with seven concentric circles to designate areas for the detailed analysis (Block, 1969).

Regardless of the technique used to analyse the detail of the prints, when it comes to the comparison stage one of two paths are taken, either the prints are compared to a previously held set of recorded prints or they are compared to latent fingerprints. By definition latent prints are those whose visibility is low unless developed by chemical or physical means. In practice, however, they are generally those left on surfaces at the crime scene, home or work place of an individual and if left in blood or grease are sometimes visible. When any part of a body contacts a surface there is a transference of materials between the body and that surface. The sweat and sebum on the surface of the skin are transferred to the touched surface in the pattern of contact, which, if it is from the fingers, will reflect the pattern of the friction ridges – a fingerprint. Various physical and chemical reagents when applied to the latent print will make it far more visible, thus allowing a photograph to be taken for analysis of the print.

As with any system some potential problems do exist.

i) Obtaining Original Prints – the state of the remains is an important consideration. In cases of burning or fragmentation of the remains there may not be enough tissue present to obtain satisfactory fingerprints. Post-mortem changes such as rigor mortis and decomposition may hinder the finger printing process or even make it impossible to complete. There are, however, techniques that allow prints to be taken from even severely decomposed bodies (Block, 1969).

ii) Latent Prints – Most problems with latent prints relate to the way in which the print was placed on the surface in the first place. Latent prints may be distorted from uneven pressure on surfaces resulting in skin folds and elongation or other distortions of the print. Often only fragments or small parts of a print are left. These fragments vary in size but may be from an area of the print that holds little information. Often the print may be smudged or smeared. Finally, the orientation of the print may be extremely difficult to ascertain, more so with palm than fingerprints, but especially if it is in any way distorted or smudged (Block, 1969).

iii) Fingerprint Records – probably the biggest limitation to this method of identification in this country. Unlike the United States, the fingerprint databases in Australia are limited to those of convicted of a criminal offence. The national database, known as the National Automated Fingerprint Identification System (NAFIS) was established by CrimTrac in 2001 with 2.4 million 'ten-print' records (CrimTrac, 2004).

Despite its shortcomings, whenever applicable, this method of identification is highly accurate and very useful in the forensic setting.

4.5 DNA ANALYSIS

Much like fingerprints, DNA can be used to identify an individual because each person's DNA, with the exception of identical twins, is unique. As such, this is another form of identification that is accepted as stand-alone, not requiring the support of any other evidence to establish a positive identification. Another similarity to fingerprints is that there is no all-encompassing national database containing DNA profiles of the entire population. This means that in order for a DNA analysis to be used in an identification a putative identification must be known so, a reference sample of DNA can be provided as a point of comparison.

There are two types of DNA found in the human body; nuclear DNA, found in the nucleus of all cells, and mitochondrial DNA, found only in the mitochondria. Both types can be the subject of forensic investigation.

Nuclear DNA

About 80% of the human genome is not gene related, that is, it does not code for a specific protein. Of this extragenic proportion about 20% consists of highly repetitive sequences of DNA and it is this part of the genome that is analysed in forensic DNA techniques. In DNA analysis a specific site, or locus, on a specific chromosome is examined. At this locus there will be a specific pattern of base pairs repeated over and over, this sequence is known as a Short Tandem Repeat (STR). It is the length of this STR that is recorded for this locus and, as chromosomes occur in pairs, also for the matching locus on the other homologous chromosome. This combination of loci with their specific lengths, known as 'length polymorphisms', will only be present in a certain proportion of the population. The numerical value for this proportion is contained in tables derived from population specific studies. This process is then repeated for a number of other sites on the sample of DNA, usually 10 to 12 loci. Using the 'multiplication rule' the chances of each of these length polymorphisms occurring in the population are multiplied together to give a final figure that indicates the chance of finding another individual with the same combination of polymorphisms. More often than not this figure will describe the combination as unique in that the chance of it occurring elsewhere in the population would be less than 1 in 'the population of the world.'

Having deduced that an analysed DNA sequence is unique, samples for comparison can then be analysed in the same way and compared to the initial sample. These samples can come from items belonging to the putative identity such as hair from a brush, or swabs from a toothbrush, mouthguard, a shoe or hat. If any of the samples match, the uniqueness of the sequence dictates that we can deduce that the samples are from the same person and as such a positive identification is made. An alternative source of comparison samples is that of a parent or sibling. While the polymorphisms will not match completely, half of them will match either a father or mother. The main shortfall with this method is that the statistical power of the analysis is lost, and the chance of the sample belonging to just the one individual putatively identified will be considerably less than 'unique', for example 1 in 20 000.

Mitochondrial DNA

Whereas each cell only has one set of nuclear DNA, the same cell may contain tens of thousands of mitochondria, each containing a copy of the same molecule of mitochondrial DNA. For this reason it may be impossible to isolate the required amount of nuclear DNA from a badly degraded piece of tissue, but quite easy to extract enough mitochondrial DNA for analysis from the same tissue sample. Such degradation occurs in bodies that have been incinerated, are badly decomposed, or have been skeletonised for an extended period of time.

The mitochondrial DNA molecule, at about 16 600 base pairs in length, is much smaller than the three billion base pair length of the nuclear DNA of the human genome. Another significant difference from nuclear DNA is that mitochondrial DNA has no significant regions of highly repetitive STRs. For this reason only two short (350-400 base pairs each), highly variable regions of the molecule, known as HV1 and HV2 in the D-loop, are analysed for the sequence of base pairs in the region. This sequence of base pairs is known as a sequence polymorphism and is not unique but will only occur in up to about 5% of the population whether they are related or not (Fourney, 1998). The fact that D-loop polymorphisms are not unique means that their analysis is not overly useful in a criminal case as it provides for a reasonable doubt to exist, in that the sample could belong to many other individuals and not just the accused. However, mitochondrial DNA analysis often provides enough information for a coroner to establish a positive identification.

Mitochondrial DNA is not unique to the individual but is maternally inherited. As such, sequence polymorphisms from an individual can be matched to a mother, sibling or any other maternal relative. This fact proves very useful in the identification of historical remains, such as the recovery of skeletal remains where no reference sample from the deceased can still be obtained. This technique is often used by the United States Military in the recovery and identification of skeletal remains from deaths occurring during World War II, the Vietnam and Korean Wars and other actions. In such cases a mitochondrial DNA sample is obtained from a putative maternal relative of the deceased and matched against a sample from the skeletal remains. It was in this manner that the body disinterred from the Tomb of the Unknown Soldier from the Vietnam War at Arlington National Cemetery in the United States was positively identified (Office of Assistant Secretary of Defense, 1998).

Comparative DNA analysis provides a very effective yet still costly method of forensic identification. The other significant shortfall is that of timeliness. The cases being analysed must be separated by time and space if any cross-contamination effect is to be discounted in a positive match. In the Disaster Victim Identification (DVI) operation conducted in the aftermath of the Bali bombings in October 2002, approximately 50% of all victims were identified by dental means alone within two weeks of the blast. It was not until this time that the first significant amount of DNA analyses results were received and able to be used for positive identifications (Author, 2002).

As technology improves and the speed of DNA analysis increases, while its cost decreases, the use of this technique will surpass all others as the first choice in forensic identification. In the mean time, in cases where no fingerprint or dental evidence exists, it is often the only recourse for a positive identification.

4.6 CRANIOFACIAL TECHNIQUES

Craniofacial identification involves the analysis and comparison of the morphological features of both the skull and face. It can be divided into three main areas; that of facial recognition, skeletal/facial comparison and facial reconstruction.

Facial recognition

This is a skill that humans develop at a very early age, but it is in the automation of the process that recent advances lie. The basis for the techniques is the computer-assisted comparison between two facial images. These images may be from photographic, video or other imaging sources such as anthropometric scanners, or from medical imaging techniques such as Computerised Tomography (CT) and MRI. Areas where the technology is used include comparisons between images of an alleged criminal and closed-circuit video footage of a criminal act such as a robbery; comparison between real-time images of a face and an image database for security checks; and post-mortem identification where, although the deceased is potentially visually identifiable, no acquaintances are available to make such an identification and ante-mortem photographs are to be used as a point of comparison.

Direct comparison of images is the mainstay of this field. However, techniques can be used to modify images to allow for ageing of an individual. Such technology has been used in missing persons cases where a period of some years has elapsed since the last photo was taken. In this way, an image of the missing person can be rendered to appear as the person would in the present day. This technique can be extremely useful, particularly when considerable growth related changes have occurred in the interim period, as may be the case with a missing child.

The frequency of use of all these techniques is increasing as the advances in development of the underlying technology continues. These advances allow the processes to be undertaken more accurately and more efficiently than before.

Skeletal/Facial comparison

The comparison between the human skull and the face can provide valuable information to be used in the identification of an individual. Much of the work in this area has been based on studies undertaken over 100 years ago. The work of Welcker and His in the late 1800s provided a significant amount of information, not only about soft tissue thickness but also about the relationships between the underlying bony landmarks of the skull and soft tissue features of the craniofacial complex (Grüner, 1993).

The techniques used in this field centre around the superimposition of an image of a human skull with an image of the face of the living person from whom the skull supposedly originated. The superimposition can be undertaken using either video or computer techniques. This allows for the two images to be overlayed in such a way that their orientation allows for a direct comparison of the hard tissues of the skull and associated soft tissue features of the face. Further, these techniques also allow for direct comparison of the dentition of the skull and any dentition showing in the ante-mortem images.

Quantitative morphological comparisons can also be undertaken between a skull and an image, provided that any scaling or distortion of the ante-mortem image is accounted for. In this way, physical measurements of the bony landmarks of the skull can be matched against estimated measurements of the overlying facial features. In cases where ante-mortem radiographs such as lateral cephalograms are available, the same views can be reproduced post-mortem and compared to each other using the same standard craniometric measurements as those that are widely used in orthodontics. It has been reported that the craniometric individuality of a human skull is as distinctive as that of fingerprints (Lambrecht et al., 1993).

Facial reconstruction

This area of craniofacial identification involves the virtual or actual addition of material to a skull to sufficiently replicate the estimated ante-mortem soft tissue features. In this way, a likeness of the ante-mortem appearance of the individual is reproduced. This reconstructed likeness can be used to help identify the individual by direct comparison to existing ante-mortem photographic, video or drawn images, or to personal recollections of the face of the deceased. Acknowledged deficiencies in these techniques are that hair and eye colour, body fat levels, ear and nose size and shape are only guessed at. These are features whose variation may have a significant impact on the appearance of the result.

Facial reconstruction methods are by no means precise, and many studies have been undertaken to establish the degree of accuracy of these techniques. There has been no general consensus among these studies with the results ranging from 'slight or no resemblance' in studies by Eggeling (Eggeling, 1913) and Stadtmüller (Stadtmüller, 1923) right through to a 'definite resemblance in all cases' by Gerasimov (Gerasimov, 1971). In 1981

Caldwell undertook a study of the reliability of reconstruction techniques used in forensic cases, and found that such techniques were useful and reliable, reporting success rates of about 59% (Caldwell, 1986). In 1993 Helmer et al. undertook a study to answer the question, ‘How good is the resemblance between the reconstructed skull models and the living persons?' They found that, noting the subjectivity of any such assessment, in the great majority of cases the similarities are very strong (Helmer et al., 1993). In the light of such results the field has perhaps best been described by George as 'scientific art' (George, 1993). It is a point worth noting that professionals in this field often refer to their techniques as facial approximation and not reconstruction.

In physically building up the soft tissue features with a substance such as modelling clay, two main techniques are used in order to provide a reasonable approximation of the ante-mortem appearance. While it is possible to use the actual skull, it is usual practice to use a duplicated model. The first technique relies on reproducing the anatomy of the facial muscles to provide the underlying contour for the final ‘skin’ layer. The second, more quantitative and more widely used method involves building up the soft tissue to predefined depths at many locations over the entire skull. These tissue depths have been recorded in many studies on the subject, but are population/race specific. As such it is important to know the suspected age, sex and race of the skull, much of which can be estimated from the skull by anthropological methods.

While the above techniques are widely used, recent improvements in computer technology have allowed these techniques to be replicated in a virtual environment. The same tissue depths can be used to build up virtual soft tissue. The advantage of this system is that literally hundreds of combinations of minor variations can be rendered in a very short space of time. These variations may involve not only the soft tissue features such as ear size and eye colour but can also include variations in tissue depth to replicate varying levels of body fat or racial background. A combination of the real and virtual methods is yet another technique in use today. The soft tissue is physically built up on the skull, but the highly variable soft tissue features such as ear and nose size, and eye and hair colour are left off. This basic build-up is then imaged and placed on a computer where any combination of these other features can be added and changed quickly and easily. In this way a number of different approximations can be produced from a single skull, with the hope of increasing the chance that the final results will be recognisable.

These methods continue to be used to assist police in investigations throughout the world. While there is some disagreement over the accuracy of approximations, in all cases some success is better than no success at all.

4.7 DENTAL

Identification by dental means is often used as it is fast, cheap, reliable and is one of the few methods that is accepted as a stand alone form of identification by the Coroner. As mentioned previously the mode of identification can take on one of two general forms. The first of these areas referred to by Sassouni was that of the reconstructive techniques, used where the suspected identity of the victim is not known (Sassouni, 1963). This means that although no ante-mortem records are available for comparison there is still much information that can be gained from the dental examination. A profile of the victim that may eventually lead to their identification can be well augmented with deductions from dental information. Details such as whether or not they received regular treatment, and if so was it complex and expensive or just routine may give an insight into the socio-economic status of the individual. Occupational or lifestyle markers can give further clues; and age at the time of death, sex, and race, can all be deduced to varying degrees of accuracy. These details will give, at best, a possible profile of the victim. If the profile allows the investigators to arrive at a list of possible identities, the procedure will then move into the second area.

This second area that Sassouni referred to was the comparative techniques, which are used when a possible identity of the victim is already known (Sassouni, 1963). This allows for the comparison of the result of the post-mortem examination to any ante-mortem records obtained. These ante-mortem records are often diverse in nature but may include written dental records, dental charting, laboratory instructions, dental radiographs, casts or impressions of teeth, old or new prostheses made for that patient, bite records, photographs (either clinical or personal showing the teeth), medical radiographs and other images such as CT or MRI scans, and personal recollection by either the dentists or those who were acquainted with the victim. From each of these sources a significant amount of information can be obtained about any treatment undertaken. Such details may include the timing of that treatment, the prevalence of any oral diseases or other anomalies and the existence of any previous treatment by other unknown dental practitioners.

Regardless of the availability of ante-mortem records, all cases where dental information is used as the identifying means require a thorough post-mortem examination. The purpose of this examination is to obtain as much information as possible about the dentition and oral cavity of the deceased. It is this information that describes the characteristics that contributed to the uniqueness of the individual. It is this uniqueness that makes a positive identification possible.

The post-mortem examination should be a comprehensive one, even when only dental fragments are recovered. Much information can be obtained from a full charting and written description of the dentition or of the fragments recovered. Periapical radiographs of all teeth and tooth bearing areas are considered necessary, as well as photographs and impressions if required.

Sopher has suggested that this post-mortem examination must include the following 12 parameters (Sopher, 1976):

4.7.1 Number of teeth

The presence and/or absence of teeth is extremely important. The number of possibilities that exist for the combination of teeth missing or present may well be enough to obtain a positive identification. It is important to establish whether the teeth were lost ante- or post-mortem or around the time of death (peri-mortem). This will help establish the pattern of treatment undertaken with regard to any exodontia, and closer examination of any tooth sockets may give an indication as to the time lapsed since this treatment.

4.7.2 Restorations or prostheses

The presence of restorations and fixed prostheses is perhaps the most easily identifiable of any unique characteristics. Although the prevalence of restorations, as with missing teeth, may provide enough information, it is the type and shape of the restorations that is unique. The radiographic examination in conjunction with the visual examination enlightens us as to these properties of the restoration.

The materials used in restorations vary greatly- from amalgam, gold or other precious metals which are radiographically opaque, to porcelain, acrylic or composite resins whose radiopacity differs significantly.

The shape of the restoration is determined by many factors. With the aim of restoring the natural occlusion, the dentist who placed the restoration initially carves the contour of the occlusal surface. Over time, as the materials are subjected to occlusal forces, they wear down and may substantially change shape. Again, in an attempt to reproduce the natural form of the original tooth, the dentist also contours the buccal and lingual surfaces of any placed restoration. The contour of the mesial and distal surfaces is usually determined by the shape of the area of contact with the adjacent tooth. In cases where the adjacent tooth is missing, the dentist will shape it as for the buccal or lingual surfaces. Finally, the shape of the pulpal or pulpo-axial surfaces (those in direct contact with the tooth in which the restoration has been placed) is determined by the shape of the cavity preparation drilled by the dentist and is therefore extremely variable.

Fixed prostheses such as veneers, crowns, inlays, onlays and bridges are also extremely variable in construction and placement. Although largely radiopaque, therefore masking the morphology of the underlying tooth preparation, visual examination of these prostheses often reveals much about the materials and techniques used. This information may prove extremely useful if it can be compared to the details of the treatment that may be obtained from the deceased's dentist or dental laboratory.

The presence of any removable prostheses should also be noted. If these are not present, evidence of their existence may be gained by examination of the remaining dentition and surrounding soft tissues. Missing teeth, tooth preparation of teeth adjacent to, or remote from, edentulous regions and permanent depression in the soft tissues of the palate from denture food lines may all be indications that the deceased had worn a partial denture at some stage.

The recent increase in the use of osseointegrated implants has provided yet another facet to dental identification. The type, shape, position of placement and orientation within the alveolus all should be examined and noted. The construction of the prostheses placed on these implants is also often unique. As with conventional fixed prostheses the materials, type, shape and shades of these implant retained prostheses also highly variable and therefore important.

4.7.3 Dental caries

The recording of the presence of dental caries is useful for a number of reasons. Firstly, it provides a point of comparison to any dental charts obtained from the deceased's dentist. Although full dental charting of all existing restorations is not universally practiced among the dental profession, it is common practice to chart existing caries as this is the best indicator of what restorative treatment is required. Secondly, the number and size of any carious lesions present may be useful in estimating the time elapsed since the victim had last seen a dentist for treatment.

4.7.4 Malposition and malrotation

Any deviations from the normal in the position of the teeth should be noted. These can be divided in two broad categories. Firstly, the case where the tooth remains located in roughly the site within the jaws where the tooth would normally be located, but its orientation within that site is unusual. Secondly, the case may exist where the tooth is located at a site different to that where it would normally be found. Obviously, these cases are not mutually exclusive as there may be some overlap. The first category will include such changes as rotation, inclination, proclination and mesial or distal tipping of the tooth. The second category occurs as a result of either ectopic eruption of the tooth or it moving bodily within the alveolus after eruption. This post-eruption movement occurs as a result of masticatory forces or orthodontic treatment that move the tooth into a pre-existing adjacent space. This movement often occurs to adjacent teeth simultaneously as they all shuffle forward (i.e. mesially) as a block. This results in a phenomenon known as packing and sometimes results in confusion when designating teeth for charting that have moved into a location of a similarly shaped tooth. The two most common examples of this are a second premolar drifting into the space from a missing first premolar, or a second molar drifting into the space left by a missing first molar. This phenomenon is not limited to these examples, as it can occur throughout the dentition especially in the lower incisor region. In some cases of orthodontic treatment the teeth are all shuffled back (i.e. distally) depending on the treatment required.

4.7.5 Peculiar shapes of teeth

Ante-mortem traumatic fractures of teeth are a permanent record of previous injury and provide a point for comparison. Shapes of fractures and fractured teeth can be compared radiographically, photographically, and/or by the physical comparison of ante-mortem casts, if available. These comparisons may even be made if the fracture has been repaired ante-mortem.

Crowns

Malformation of the crowns of teeth is relatively uncommon but does occur. Some of the more common malformations include:

i) Third Molars – these have the most variable crown forms of any of the teeth and can vary from small peg-shaped crowns up to large multicusped malformed version of regular molar anatomy;

ii) Permanent Lateral Maxillary Incisors – may occur in a peg-shaped form. This formation is present in about 1-2% of the population;

iii) Gemination or Twinning – this appears clinically as fused teeth but the tooth has one common root and pulp canal system. Occurs more frequently in the anterior maxillary deciduous dentition than anywhere else;

iv) Fusion – clinically appears similar to gemination but will have two separate root and pulp systems;

v) Hutchinson's teeth – occurs in both dentitions as a result of prenatal syphilis. They have the appearance in the incisors of being screw shaped, broad cervically narrowing to the incisal with a notched incisal edge, whereas posteriorly the occlusal surface of the molars appears to be made up of small tubercles with little or no distinguishable cusps, known as 'mulberry molars';

vi) Accessory cusps – any teeth can exhibit additional cusps or enamel protrusions. This includes such features as enamel pearls, small nodules of enamel with a dentine core commonly found on the buccal furcation of molars and the distal of third molars; and Talon Cusps which are small enamel projections in the cingulum area of anterior permanent teeth;

vii) Size variations – true microdontia or macrodontia is rare but does exist. It is not uncommon to mistake over- or under-development of the jaws for either of these conditions respectively; and

viii) Shovel-shaped maxillary incisors – the teeth have accentuated cingula and marginal ridges lingually providing a shovel shaped appearance (Baker, 1973; Woelfel and Scheid, 1997).

Roots

Subgingivally there is enormous variation in the structure and number of roots each tooth has. Usually observed radiographically the number, shape and orientation of the roots of the teeth should be noted for later comparison. The following abnormalities may occur and are very useful in ascribing uniqueness to a dentition when they do:

i) Dilaceration – a severe bend or distortion of a tooth root and crown resulting in an angle between the two of more than 45°;

ii) Flexion – a curvature, twist or bend (less than 90°) of a tooth root;

iii) Dens-in-dente – due to the invagination of the enamel organ in crown formation. It most often occurs in maxillary lateral incisors and appears as a deep crevice in the cingulum area;

iv) Concrescence – similar to fusion but occurs after the teeth have erupted. The two roots of two adjacent teeth grow together through the deposition of cementum only. This occurs most commonly in the permanent maxillary molars;

v) Segmented root – where a root is separated into two parts;

vi) Dwarfed roots – often hereditary, the crowns appear normal but the teeth have abnormally short roots;

vii) Hypercementosis – excess formation of cementum after eruption. It may cause the roots to appear bulbous or cause webbing in multirooted teeth; and

viii) Accessory roots - these are most common in the permanent dentition and often exhibit dilaceration or flexion (Baker, 1973; Woelfel and Scheid, 1997).

There are also variations in tooth morphology that occur regularly and although they may not identify an individual on their description alone they can be very useful when used in conjunction with other information. For example, they can often be used to corroborate other anthropological evidence of a specific racial grouping. These morphological features include: shovel-shaped incisors which are found far more frequently in the Mongoloid races, taurodontia, which mainly occurs in American Indians and Eskimos but at an incidence of less than 1 in 1000, and the fifth cusp or cusp of Carabelli on the first permanent maxillary molar which is particularly prevalent in, but not exclusive to, Caucasoid Europeans (Lasker and Lee, 1957).

Today, as community awareness of the need for preventive dentistry is on the rise and incidence of caries falls, we have the situation arising whereby more and more people are not requiring any restorative dental treatment at all. With the falling incidence of restorations, tooth and root morphology is becoming increasingly important in the identification process. As with the previously mentioned morphological features, if there is no evidence of disease or dental treatment, it often falls to this area of detail to provide the necessary points of comparison.

4.7.6 Root canal therapy or endodontics

Endodontic treatment is yet another way in which the dentist may have left a distinctive identifying restoration within the dentition. Whether the shape of the root canal itself is changed by instrumentation during the endodontic procedure or not, a distinctive shape of the restoration is created. Comparison of pre- and post-operative radiographs to the post-mortem radiographs is extremely useful in identification. Where no ante-mortem radiographs exist, written records often provide enough detail to make a comparison, using such detail as root number and length. Again, the prevalence of this treatment in the deceased's dentition can often be used as an identifying feature.

4.7.7 Bone patterns

Radiographically the patterns formed by the bony trabeculae within the cancellous bone, particularly in the mandible, can often be used as unique identifying features. In the maxilla the bony patterns of the lower borders of the maxillary sinuses can equally be used and should therefore be carefully noted. At least one paper has commended the use of the morphology of the frontal sinuses as a point of comparison for forensic identification of individulas (Harris et al., 1987a). However, a later study of frontal sinus morphology by the same researchers found that the differences between sexes or racial groups were not sufficient to discriminate between cases on this basis (Harris et al., 1987b).

Other patterns within the bone may also be revealed radiographically. These include, among others: the patterns of healing sockets, previously healed fractures and the existence of cysts or other bony pathology.

4.7.8 Complete dentures

The shape, size, materials and shade of the artificial teeth within a full denture are details that many laboratories, if not dentists, keep a record of. Any repairs made to the denture should be noted as well as any unique identifying shape or other features. Although most dentures today are made of acrylic resin with acrylic resin teeth, it is worth noting any material deviations from this, for example, metallic inserts in the base plate for strength.

It has been suggested in many a forum that a universal system of denture marking be adopted to label dentures (Borrman et al., 1999; Thomas, 1984). In the event of the deceased requiring post-mortem identification, the denture could then be traced to the dentist who constructed it and the deceased identified. There are many suggestions for different systems or codes with which to mark the dentures (Borrman et al., 1995; Rotzscher et al., 1999; Thomas, 1980; Thomas et al., 1995; Millet and Jeannin, 2004) but none that has been agreed upon universally. In light of the fact that the international dental community cannot yet agree on a universally accepted system of dental charting it seems unlikely that a universal system of denture marking will be agreed upon in the near future. It is also worth noting that in many instances, regardless of the presence of a unique marking system or not, a removeable denture may well be considered 'property' and, therfore a transferable item that can only be used to cooborate an identification, not establish one.

4.7.9 Relationship of the bite

The relationship of the upper to the lower arches in occlusion should be noted. Any deviations from the standard Angles Class 1 classification, including isolated variations such as crossbites and excessive overjet or overbite should likewise be noted.

4.7.10 Oral pathology

Although not often a unique identifying feature, the presence of oral pathology may lend support to an identification. It is important to not limit the search for oral pathology to the soft tissues, although this may seem the most obvious place to do so. Periodontitis is an example of a very common disease affecting both hard and soft tissues, and its presence may prove useful in discriminating between cases in need of identification. On the other hand, some congenital defects such as amelogenesis or dentinogenesis imperfecta, that affect only the hard tissues, are quite rare and may be of greater value in identifying an individual.

That is not to say that soft tissue pathology is not important. On the contrary, soft tissue manifestations of oral disease can be of great value themselves especially if their presence and detailed description has been noted by the victims dentist.

4.7.11 Occupational changes and socio-economic pattern of the dentition

Some dentitions may exhibit unusual wear patterns which may help an identification in a reconstructive manner by contributing to the profile of an unidentified body. For example, severe generalised tooth attrition is common among workers continually exposed to atmospheres containing abrasive dust. In making such inferences, care should be exercised as similar patterns may also occur in the general population as a direct result of nothing more than severe bruxism. Certain other habits may also leave permanent vestiges that may help develop a profile of the individual – for example, chronic pipe smoking or long-term bagpipe playing may result in an obvious unilateral bimaxillary wear pattern, and notching of the upper incisors has been frequently described in hairdressers who habitually hold hairclips in their teeth before placing them in a clients hair (Whittaker, 1994).

The prevalence of caries in an individual may give an indication of their socio-economic status, as it is well documented that those people in the lower socio-economic groups tend to place a lesser value on the importance of dental care, and as such are less likely to seek routine dental treatment (New South Wales Department of Health, 2001); the converse is true for those in the higher socio-economic groups. Those that are more socio-economically disadvantaged seek dental treatment less often and have greater rates of untreated caries than those less disadvantaged (New South Wales Department of Health, 2001). This information may be useful in helping to narrow the field of search for the putative identity of an unknown victim, by helping to provide an indication of their socio-economic background.

4.7.12 Lip Prints

It has been suggested that lip prints may be used as a unique identifier in much the same way as fingerprints (Suzuki and Tsuchiahashi, 1970). A review by Ball found that although lip prints have been used in court in isolated cases, there needs to be far more research to support the claim of uniquness attributable to any such evidence (Ball, 2002).

4.7.13 Sex and race determination

While this area is normally the realm of the forensic anthropologist, there have been a number of studies that have used the dentition to help determine the sex and race of a body. Sexual dimorphism in the dentition is extremely variable, but generally speaking female teeth are slightly smaller especially in the mesio-distal diameter of the permanent molars. Many studies have been undertaken to determine sex from the teeth (Bailit and Hunt, 1964; Black, 1978; Ditch and Rose, 1972), however, Krogman and Iscan warn against using these methods singularly to determine sex (Krogman and Iscan, 1986).

The assessment of race from teeth is also a method that should not be heavily relied upon, but may corroborate other anthropological findings. Lasker and Lee published a summary of racially prevalent dental traits (Lasker and Lee, 1957). These features included: the presence of shovel shaped central incisors in 85% of Chinese, Carabelli's cusp in 35% of Caucasoids, 8% of Mongoloids were found to have an extra distolingual root on the first or third mandibular molars that is rarely found in other races, and enamel extensions are more common and roots shorter and less splayed in Caucasoid teeth. These features may help provide an indication of race, but it should be noted that their presence or absence is not always clear-cut, and that there maybe a gradation of development of them. This further complicates any attempt to determine race solely from the dentition. Although much less effective than skeletal measurements, tooth size measurements have been shown to discriminate between living populations (Falk and Corruccini, 1982). The reduced effectiveness of tooth measurements over other skeletal methods to discriminate between races is due, in part, to the inter-correlations between crown diameters (Harris and Rathbun, 1991). As a result these measurements duplicate one another in discriminatory function which, in turn, reduces their value for identification in forensic cases (Kieser, 1990). Despite this shortcoming, Harris and Rathbun also found that general differences in the pattern of crown diameters do exist between populations (Harris and Rathbun, 1991). Therefore, as long as the researcher is aware of the limitations, tooth size can be used as an indicator of race.

Regardless of the type of identification or the methods used, it is evident that a large amount of information may be obtained by examining the deceased and their property. The more detailed and accurate the examination is the more information that will be obtained. Whether it be for reconstructive or comparative purposes any or all these methods may be useful if not in positively identifying the victim, then in corroborating the other identifying evidence.

Chapter 5

AGE ESTIMATION

The parameters for forensic dental examination suggested by Sopher (Sopher, 1976) are quite comprehensive. However, the area of age estimation is conspicuous by its absence. Sex and race determination are important but cannot be predicted with the accuracy that age can. It is a parameter that once known can prove extremely useful in, if not identifying an individual, then in greatly narrowing down the field of potential identities.

The methods of estimating age at time of death are many and varied. In this chapter the most common of those methods will be reviewed. The main exception to this review will be those methods of age assessment based on the degree of calcification of the dentition. As it is these that are most useful when the victim is under the age of 15, and are therefore particularly relevant to this treatise, they will be examined in detail in the following chapter.

Age at death can be estimated from either the cranial or post-cranial skeleton. For the purposes of this review they will be grouped in a different manner, being that of dental and osteological methods. Before launching into an analysis of the various means of ageing available to the investigator it is important to define the concept of age.

Generally speaking when we use the term age we are referring to the chronological age of the individual or object, that is the amount of time that has elapsed since the person was born, or since the object was made. From a forensic view point, when we wish to know the age at time of death we are actually asking for the chronological age, the time elapsed between the birth and death of the individual. It is impossible to answer this question precisely without knowing the date of birth and date of death of the individual in question. Fortunately, in cases where this information is not available, an estimate of the age at time of death can be made based on the biological maturity of the body.

Frank defined the process of maturation as 'a series of successive transformations through time' (Frank, 1950). He then states that this occurs until the adult state is achieved. A broader view of this process that is not limited by the achievement of the adult state would seem more appropriate in light of the fact that biological maturation continues throughout life and that the term maturity should be used as a general concept for any specified stage during this process (Taranger, 1976). Thus there can be many different measures of maturity.

As it is biological maturity that allows us to best predict chronological age we shall limit the discussion to this area. Biological maturity can be measured in any of four physiological divisions: somatic, skeletal, sexual and dental. Somatic maturity involves a further subdivision into morphological, physiological and biochemical facets. Sexual maturity revolves around the onset of menarche and the pubertal growth spurt. Skeletal or osteological and dental maturity can be assessed in many different ways, as previously alluded to.

From examination of the level of biological maturity an estimate of the somatic, sexual, dental or skeletal ages can be arrived at. As these biological ages are in themselves only an estimate, the degree of accuracy of this estimate should be noted. The next consideration is the degree of correlation between a measure of biological maturity and chronological age. That is, when making an inference as to the chronological age from this information it is critically important to take into account the degree of correlation and the mean error involved in this step. Some methods may provide better estimations of age than others. Further to this, it is common practice to rely on more than one method of age estimation as combinations of methods often lead to improvement in the accuracy of the estimations with diminished error.

Many studies have been undertaken in an attempt to find a correlation between these measures of biological maturity. Researchers have found a high degree of correlation between somatic, sexual and skeletal maturity (Demirjian et al., 1985), and it is thought that these systems have a common controlling mechanism. It is the relationship between skeletal and dental maturity that is open to debate. Some researchers have found relatively high correlations between skeletal and dental maturity (Demisch, 1956; Hägg and Taranger, 1981; Liliequist and Lundberg, 1971), while others have found a low or insignificant correlation between the two (Acheson and Dupertius, 1957; Lewis and Stanley, 1960; Tanner, 1962). A study by Garn et al. (Garn et al., 1965b) showed that relationships between the timing of tooth formation and somatic development, though in the expected direction, are of a very low order of magnitude. Other studies have also noted that dental maturation is relatively independent of somatic, skeletal or sexual maturation (Edler, 1977; Holtgrave et al., 1997; Kosowicz and Rzynski, 1977; Midtbo and Halse, 1992).

It has been suggested that these two systems are controlled independently of each other as they have differing embryonic origins (Demirjian et al., 1985). On one hand we have skeletal, somatic and sexual maturity pertaining to tissues of mesodermal origin under control of pituitary and gonadal secretions, whereas on the other hand we have the dental structures of ectomesenchymal origin, the developmental controlling mechanisms of which little is known. Regardless of these interrelationships, it is the relationship of each measure to chronological age that is of forensic importance.

5.1 THE DENTITION AND THE ESTIMATION OF AGE

Examination of the dental tissues as a method of estimating the age of an individual is a practice that dates back to the early 19th century. At this time in the United Kingdom it was law that children under the age of 7 years could not be punished for committing a crime. It was, therefore, important to establish the age of the accused child. As the registration of births was not practised, the courts began to rely on age estimates based on the dentition. In 1836 Thomson, a medico-legal expert, suggested that 'if the third molar has not protruded there can be no hesitation in affirming that the culprit has not passed his seventh year' (Miles, 1963b). The ‘third molar' referred to here is actually the third molar in the eruption sequence after the first two deciduous molars, i.e. the first permanent molar.

Another example of this forensic need occurred in connection with the Factory Act of 1833. This Act made it illegal to employ in the mills any child under 9 years-of-age and further restricted the working hours of those aged between 9 and 13 years. The exploitation of child labour was rife, as the only evidence the court demanded at this time was that the child should be 'of ordinary strength and appearance of a child of at least 9 years-of-age'. In 1837 a dentist, Edwin Saunders, presented a pamphlet titled 'Teeth A Test of Age' to the English Parliament. In it he pointed out the value of using the dentition in the assessment of age, quoting the results from a study of 1000 children. By including tables and detailed instructions he proposed that even relatively untrained people could assess the age of children for the forensic purposes of the Act (Miles, 1963b).

Today the reasons for estimating the age of an individual may have changed but the requirement still remains. Our understanding of age related changes in the dentition has grown considerably since the 19th century and this has resulted in many new and varied methods of assessing the level of dental maturity from which we can estimate chronological age. The accuracy of some of these methods may vary greatly, not only from one to the other, but also within a given method depending on the researcher. Meanwhile some methods have produced encouragingly consistent results. Below the more popular of these methods are examined.

5.1.1 Eruption Times and Tooth Counts

Observation of the number of teeth present in the oral cavity is a technique used widely but which, as we shall see, has its limitations. Although there are any number of variations, the basic principles are that of examination of the number and type of teeth that have erupted and comparison of this with either tables or diagrams that relate those observations to a dental age. This technique is based on the assumption that different teeth erupt at different ages, and by observing which teeth have erupted one can estimate the dental age of the individual.

There are a number of considerations which should be noted: eruption times are variable and are affected by a diverse range of factors (Fanning, 1961; Moorrees et al., 1963b), the technique is limited to those periods when teeth are erupting (i.e. 0-3 years for the deciduous and 5-14 years for the permanent dentition), and the various techniques rely on different definitions of the term eruption.

Tooth eruption is an ongoing process that continues throughout life. It is the movement of the tooth towards the occlusal plane. Initially, as the tooth is forming within the bone of the maxilla or mandible, it moves through the bone in the direction of the oral cavity. Once the tooth pierces the gingiva it will continue to move towards the occlusal plane. Once in occlusion the tooth will wear at the occlusal surface and it is this process that contributes to the ongoing eruption of the tooth throughout life (Marks Jr and Schroeder, 1996; Picton, 1957). Despite this understanding of the process most studies consider a tooth to be erupted when it first emerges into the oral cavity. A better description of that point may be that of the term tooth emergence or clinical emergence even though the many studies that are based around this point in the process refer to it as eruption. Having said that, some authors have made a point of delineating between eruption and emergence as it is critical in defining the point at which teeth are to be counted in their assessment. Shumaker defined a tooth as being considered erupted 'when it had reached the plane of occlusion' (Shumaker, 1974); while in a different study Carr regarded a tooth as erupted 'if any portion of the crown was visible through the tissues' (Carr, 1962); and still Gron, in her study, considered a tooth erupted if 'it had just pierced the gingiva, but was no more than 3mm from the gingival level' (Gron, 1962). Each definition, though different, is important as it outlines the assessment criteria for each of their respective techniques.

The results of studies in this area are even more diverse than the definitions used in them. A study by Hägg was based on emergence as a criterion for assessment and found it to be a reliable indicator of age, giving errors of ±4 months for assessments based on deciduous teeth and ±3 years for those done on permanent teeth, both at the 95% confidence interval (Hägg and Taranger, 1985). Despite these results he also found that emergence could be affected by infection or pathology, trauma, crowding, extraction, and the presence of supernumerary teeth. Foti obtained a similar result reporting prediction errors of ±3.5 years at the 95% confidence interval for a regression model based on a sample of 6- to 20 year-olds (Foti et al., 2003). Other researchers have found that the correlation between tooth eruption and age was not strong enough to base age estimates on them alone (Towlson, 1990). Some have found that the error increases with the increase in the number of teeth present, i.e. with age (Kaul and Pathak, 1988) and still another has found, in a review of 42 separate studies, that it is quite an accurate method for use during the 6 to 30 month period of deciduous emergence and that it seems unaffected by sex or race (Townsend, 1990). Despite the obvious controversy that still exists as to the usefulness of this method, there are some points that many of the researchers in this area have agreed on, namely: that eruption times are far more variable in timing than skeletal maturation (Nolla, 1960; Van Der Linden, 1979), that tooth formation is superior to tooth emergence when used in the assessment of dental maturation (Moorrees et al., 1963a; Nolla, 1960), and that it is inadvisable to assess total maturation from one tissue system alone (Demirjian et al., 1985; Krogman and Iscan, 1986; Moorrees et al., 1963a; Tanner, 1962).

5.1.2 Aspartic Acid Racemization

This technique was first suggested by Helfman and Bada in 1976 and is based on the fact that aspartic acid molecules in tooth structure undergo a first order chemical reaction over time that is consistent, linear and measurable (Helfman and Bada, 1976). From these measurements, an estimation of age may be calculated. As this change occurs throughout life this method can be used on all age groups after the teeth have been formed.

Aspartic acid has both an L- and a D-enantiomer, different configurations of the same molecule. It is only the L-form of this acid that is used in the production of collagen, and is incorporated into collagen as it is laid down in the body. Once the dentine becomes mineralized no more of the L-enantiomer can be incorporated into that dentine. Over time the L-enantiomer undergoes a conversion, or racemization, to the D-enantiomer. This conversion is time dependant, so measurement of the ratio of D:L aspartic acid will give an indication of the time that has lapsed since the dentine was laid down and the ratio was zero. From this estimate of time the chronological age of the individual may be ascertained with some degree of accuracy (Helfman and Bada, 1976). There are other tissues in the body that contain collagen, but they undergo a turnover of this tissue, even hard tissues, which allows further incorporation of L aspartic acid with the new collagen, thus rendering the ratio measurements useless. Not surprisingly, the other metabolically stable hard tissues; enamel and cementum, are also useful in this technique, although the correlation between the D:L ratio and dental age is not as high as for that of dentine (Ohtani, 1995). There are also other amino acids incorporated into collagen but it has been found that the racemization of aspartic acid occurs in much greater, and hence more measurable, amounts.

The correlation between the ratio of D- and L- forms and the age of the tooth has been shown to be high. In the initial study by Helfman and Bada they found a correlation of r=0.979 between the D:L ratio and dental age. Further studies have duplicated and improved upon these results. A correlation coefficient of 0.97 and a mean error of ±12 years in the prediction of age at the 95% confidence level was found in a recent study (Mörnstad et al., 1994a), which comes close to the accuracy obtained by other methods of age estimation. This result was improved on by Ohtani et al. in a number of studies where they reported an error of just ±3 years (Ohtani et al., 1995; Ohtani and Yamamoto, 1991). This improvement was attributed to the use of a longitudinal section of dentine as opposed to a sample obtained just from the crown. Studies by other researchers have reported comparable results (Pilin et al., 2001; Ritz et al., 1995).

It is worth noting that this technique assumes that collagen is laid down and dentine mineralized at the same specific point in the chronological age of every human. Although we know that tooth development is not precisely predictable, it is one of the more predictable events in biological maturation and therefore probably one of the better events on which to base this technique.

The other area susceptible to variation is the rate of racemization. It has been found to decrease with age increasing the mean error to ±20 years (Mörnstad et al., 1994a). A study by Ohtani et al. found that this rate also varied by tooth type and age, reporting that in the middle-aged the rate was highest in the first molars but in older age groups the second molar had the higher rates (Ohtani et al., 2003). The rate may also be grossly affected by temperature, pH and water content of the post-mortem environment (Masters, 1986). The wide range in the reported accuracy of these techniques may be attributed, in part, to varying methodologies. Waite et al. suggested that with the standardisation and optimisation of techniques a more consistent and therefore more reliable methodology would be produced (Waite et al., 1999). Such steps would further the cause for the wider use of the technique.

5.1.3 Third Molar Development

Although strictly speaking these methods are reliant on the analysis of dental development, they have been included here as they do not address the entire dentition in their assessment, unlike those in the following chapter. Many studies have been undertaken on the correlation of third molar development and chronological age, but as the third molar is the most variable of all the dentition (Anderson et al., 1976; Mincer et al., 1993), the results have varied considerably. On one hand, there are the studies that have shown a low reliability of the technique. A study by Thorson and Häag found such a low reliability (Thorson and Häag, 1991). In this case the authors based their assessment on the tables of Demirjian, which are specific for a French-Canadian population and were shown to be inaccurate when used on a Swedish sample (Mörnstad, 1995). However, a number of other studies have reached the same conclusions as Thorson and Häag (Kullman, 1995; Kullman et al., 1992; Pogrel, 1967). The observations made included: that there is a large biological variation in the development of third molars, that there are also marked differences in this development between populations of different regions, a geographical variation, and that most studies so far have relied on subjective assessment of the degree of development, which has been shown to be a source of error. In the 1995 study by Kullman he attempted to reduce this subjectivity by using a computerized assessment technique. Despite this adaptation of the technique he still found a low degree of accuracy.

On the other hand, studies have found analysis of third molar development to be reasonably accurate and therefore useful. One in particular obtained an accuracy of ±2.4 years at the 95% confidence level and even more amazingly ±3.6 years at the 99% level (Nortjé, 1983). However, this degree of accuracy has not been able to be reproduced by other researchers. Mesotten et al., using the Gleiser and Hunt system, found a moderate correlation between third molar development and age (R-square=0.35 females and R-square=0.38 for males)(Mesotten et al., 2003). They also reported their method accurate to about ±3.1 years at the 95% confidence level. In continuing this study they reconfirmed these findings and further found strong levels of both inter- and intra-observer agreement as indicated by the calculated kappa statistics (Gunst et al., 2003). A stronger correlation was reported by Engström, who found equivalent values for R-square of 0.60 for females and 0.73 for males (Engström et al., 1983).

It is interesting to note that a study by Mincer et al. found that the mean age for third molars to reach the stage of development categorized as 'H' by Demirjian was 20.5 years in both Negro and Caucasian American children (Mincer et al., 1993). Conversely, racial variation was found to be significant in a study by Olze, et al. who compared the rates of third molar development between a Japanese and German sample. Using the Demirjian system of assessment they found that the Germans were up to 2-3 years advanced over the Japanese at certain stages in the development of the third molar (Olze et al., 2003). Gorgani too found significant differences in the rates of development of the third molar between Negroid and Caucasoid samples (Gorgani et al., 1990).

The information from the Mincer study was later used in a courtroom trial in Malaysia to determine whether or not the accused was over 18 years-of-age and therefore liable to stand trial as an adult under Malaysian law (Nambiar et al., 1996). Following an examination of the accused by a number of dentists he was determined to be over the age of 18, as the third molars were fully formed. During the trial the Prosecutor stated that the accused was an adult under Malaysian law as this had been determined with 'absolute certainty', not 'in all likelihood' as suggested by the examining dentists. This case serves to demonstrate the potential abuse of this type of information in a forensic setting. This method of age estimation, like all others, is not precise. Human growth is subject to a wide range of biological variation and, as such, any age estimation method should be used with much caution.

5.1.4 The Neonatal Line, Cross Striations and Cemental Annulations

The impact of birth on the homeostasis of the human body is well documented. Among other effects it has been shown to produce a variation in the apposition of dentine and enamel in the developing dentition. This transient variation can be seen histologically as a neonatal line in the deciduous dentition and often in the first permanent molar (Schour, 1936). Massler and Schour also produced evidence that showed the rate of dentine apposition in deciduous teeth is roughly 4μm per day. Thus by a simple absolute measurement an estimation of chronological age could be made (Massler and Schour, 1946).

Along similar lines is the examination of cross striations and Striae of Retzius in enamel. Cross striations are fine transverse striations that occur along the length of enamel prisms and are thought to represent the amount of enamel laid down every 24 hours (Beynon and Dean, 1988; Dean and Beynon, 1991). A simple count of these striations from the neonatal line should give an estimate of chronological age in days. The Striae of Retzius on the other hand are coarser lines perpendicular to the long axis of the enamel prisms and are thought to be due to the near weekly variations in enamel secretion. These too could be counted and used to estimate chronological age. It was previously thought that there should be seven cross-striations between each of these striae. This was not the case and resulted in a variation in the rate of apposition of the striae of between 4 and 11 days (Huda and Bowman, 1995). Despite this variation, Huda and Bowman found the counting of cross striations to be very accurate, far more so than presently available methods. The main advantage of this method is that it requires no reference to population growth standards and is therefore widely applicable. The main disadvantages are that it is destructive and time consuming.

The obvious limit to these techniques is that they are no longer applicable once the enamel deposition is complete. However, there are two hard dental tissues that continue to be deposited throughout life; secondary dentine and more importantly here, cementum. As the cementum is deposited on the root surface it takes on an alternative light and dark variation in colour. Although the biological mechanism for this phenomenon is not well understood, it is known that it occurs in nearly all mammals, and that it is an annual variation (Charles et al., 1986). This last observation has resulted in the use of the term cemental annulations to describe the appositional pattern. Once again a simple count of the rings from a transverse section of the tooth added to the age of the eruption of that particular tooth will give an estimated chronological age. In the study by Condon et al. in 1986, they found a correlation between the number of annulations plus eruption age of the tooth to chronological age of the individual of 0.78. This rose to r= 0.87 with an overall mean error of ±6 years when teeth affected by periodontal disease were excluded from the study. These results supported those found by Lovejoy et al. in 1985, who also made the observations that the rate of apposition of cementum and hence the accuracy of the age estimates was affected by two main factors; pathology and function (Lovejoy et al., 1985a). The first of these was either in the form of periodontitis or caries. While it is reasonably obvious that periodontitis would affect the apposition of cementum, this is not so for caries. It has been hypothesized by Condon that as loss of functional loading may lead to a decreased rate of cemental apposition, then so too could pain associated with caries cause an individual to consciously decrease the functional loading on a tooth in an attempt to avoid the pain on chewing, and hence decrease the cemental apposition rate.

More recently, Wittwer-Backofen et al. conducted a validation study of the technique on 363 teeth and reported that they found the method very accurate with errors of no more than ±2.5 years at the 95% confidence interval (Wittwer-Backofen et al., 2004).

A study by Solheim in 1990 found that the correlations for some teeth were higher than that of others. He also found that there was generally less cementum on the teeth of females and that the rate of apposition of cementum decreased with age, leading to a tendency for the technique to overestimate chronological age in the elderly (Solheim, 1990). These observations supported those already made by other researchers (Charles et al., 1986; Johanson, 1971; Lipsinic, 1986; Lovejoy et al., 1985a; Stott et al., 1982). A study by Stein once again supported these findings but found that the information was more useful when used as part of a multiple regression analysis (Stein, 1994).

There have also been studies with findings to the contrary. The most notable of these found that 'determining chronological age in humans from cemental annulations is not possible' (Miller et al., 1988). This opinion was found not to be widely supported in the literature.

5.1.5 The Gustafson Method

In an attempt to devise a system to estimate chronological age from teeth in adults Gustafson came up with what is now widely known as the Gustafson Method (Gustafson, 1950). It is based on the observation of six different dental criteria, all of which undergo age-related changes throughout life. These criteria are each examined and scored on an ascending scale of 0 to 3 depending on the severity of the change. The criteria that are assessed are:

i) A—attrition—the gradual wear of enamel on the occlusal surface;

ii) S—secondary dentine apposition—age related build-up of dentine on the walls of the pulp chamber;

iii) P—periodontosis—the irregularity in the form of the cementum and root dentine caused by ongoing repositioning of the periodontal ligament;

iv) C—cementum build up—related to periodontosis where the continuous repositioning of the tooth in the alveolar bone necessitates extra layers of cementum:

v) R—root resorption—the gradual resorption of the root apex (a process little understood in terms of oral biology);

vi) T—root transparency—the tendency of root dentine in thin sections to appear transparent in transmitted light from the apex upwards (termed sclerotic dentine).

The results of these scores were then added together to give a score that was then converted via a regression line to a chronological age.

The original study by Gustafson claimed a standard error of about 4.5 years, however this accuracy has not been replicated in many studies. One such study by Miles found an error of only 3 years but this was only in 37% of cases (Miles, 1963b). Less promising results were found by Burns and Maples, who reported that only 23% of the teeth in their sample of 355 teeth could be predicted to within 3 years of actual age (Burns and Maples, 1976). A recent study by Mandojana et al. found significant differences in the values of these criteria, depending on post-mortem interval, suggesting that this important factor should be accounted for if the accuracy of this technique is to be improved (Mandojana et al., 2001). Specifically, they found translucency length, cementum apposition and secondary dentine measures showed higher values the longer the post-mortem interval, whereas other non-Gustafson measures such as tooth length, width and root area showed lower values the shorter the post-mortem interval. The authors theorised that these changes may be attributed to post-mortem changes in the biochemical and mineral composition of the tooth structure.

A number of papers have since been written analysing the work of Gustafson and some substantial faults have been found. One such paper by Maples outlined these faults, specifically that: the regression formula derived by Gustafson was wrong; he used the same sample to test this regression formula as he did to derive it; and a number of statistical errors were made resulting in incorrect correlations and errors (Maples, 1979). Maples and Rice then went on to derive a new regression formula from the original data set of Gustafson. This resulted in a mean error of about ±7.03 years. Further critical analysis of the work of both Gustafson, and Maple and Burns by Lucy and Pollard agreed with the latter's findings but went further in reworking the figures derived from the data set (Lucy and Pollard, 1995). Lucy and Pollard found the error to be more like ±15.9 years at the 95% level. Today it is generally accepted that the average error of the Gustafson method is 10 to 15 years.

Despite the above faults in his original study, Gustafson gave the forensic community a basis on which to devise other methods of age estimation. The number of variations on the Gustafson method that have been published are many. What follows is a summary of the main and most effective ones.

5.1.6 Variations on the Gustafson Method

Most of these variations have focused on the use of one or more of the criteria of Gustafson, with modifications. The first of these is that of Dalitz. In investigating the Gustafson method he found that cementum apposition and root resorption were poorly related to age. As a consequence of these findings he omitted them from further work and went on to develop a weighting of the remaining criteria based on their relative correlation to age, using regression of his results to derive predictive formula for the estimation of age. (Dalitz, 1963).

Johanson presented the second of these variations. While retaining all six of the original criteria, he changed the scoring system. Instead of just four stages of severity Johanson used seven (Johanson, 1971). He also formulated an individual regression formula for each criterion, as opposed to Gustafson who used the one combined formula for all the criteria. Using this method Johanson reported a mean error of ±5.16 years for the 65% confidence interval.

A study by Maples in 1978 attempted to assess which criteria worked best in conjunction with each other using multiple regression analysis (Maples, 1978). The most effective combination was that of all criteria, except root resorption when specifically used on the second permanent molar, and gave an error of ±5 years. However, the combination of just secondary dentine apposition and transparency gave the best overall result when applied to all teeth.

In 1980 Metzger suggested a modification of the tooth sectioning required by Gustafson. In it he used a 1mm thin section, as opposed to the 0.25mm section used originally (Metzger, 1980). His reason for this modification was to gain a more accurate assessment of the amount of secondary dentine by allowing for asymmetry in the pulp chamber.

Then in 1990, Kashyup and Koteswara Rao suggested a modification that was based on the physical measurement of four of the criteria of the Gustafson method, namely attrition, secondary dentine apposition, translucency and cementum apposition (Kashyap and Koteswara Rao, 1990). These measurements were then converted to index values which expressed the ratios of the measurements within each criteria as a decimal value. These values can then be regressed to gain an age estimate. This method reported an error of ±1.59 years. As it appears reproducible and accurate it is one of the most promising methods so far. However other researchers have not yet duplicated the results. The use of four of the measures of the Gustafson method (systematically excluding various measures) by Solheim produced a range of correlations from r=0.76 for mandibular second premolars to 0.91 for maxillary central incisors (Solheim, 1993).

An attempt to overcome the flaw in the Gustafson method of using assigned categories as values, has been suggested in yet another study (Lucy et al., 1996). This one involves the use of Bayesian analysis which specifically addresses the unique problems associated with ordinal or categorical data. The initial investigations appear promising, yielding similar results to current regressive techniques, however more research into this area is required.

Many other studies using various combinations of the criteria of Gustafson have been undertaken. Most of these were based on the assumption that decreasing or removing the subjectivity of the observations may produce a more accurate age assessment. Some authors reported stronger correlations than obtained by Lucy et al. in the treatment of the results of Gustafson, (Kvaal and Solheim, 1994a; Lopez et al., 1993; Morse et al., 1994) while others were not that far removed from them (Lamendin et al., 1992). Prince and Ubelaker used the Lamendin method on a skeletal sample of diverse origin and obtained results similar to those of Lamendin, reporting a mean error of 8.2 years (Prince and Ubelaker, 2002). A recent re-examination of the Lamendin two criteria method found, however, that his use of the Gustafson periodontal criteria resulted in a significant bias in any age estimation (Foti et al., 2001).

5.1.7 Transparency

Although this is one of the original criteria of the Gustafson method, it is the one area that has received the most attention and as such warrants its own section. The phenomenon of transparent dentine is a physiological change that occurs throughout life. It occurs as a result of the gradual mineralization of the peritubular dentine which eventually leads to the obliteration of the dentinal tubules, commonly referred to as sclerotic dentine. The difference between the refractive indices of this intratubular dentine and the extratubular inorganic matter will be equalized resulting in an increase in the translucency of the dentine (Lamendin and Cambray, 1981). The extent of this transparent zone may be measured in either sectioned or whole teeth and from this age estimated.

While Gustafson was the first to use this method many have used modifications with varied results. Miles examined longitudinal ground sections under a microscope. With the use of regression lines he then estimated chronological age with some success, finding 33% of cases were ±3 years (Miles, 1963b). In 1968 a study by Johnson found no significant relationship between transparency and age (Johnson, 1968). Two years later Bang and Ramm developed a system based on the Gustafson method but involving measurement of the transparent zone, not just subjective observation (Bang and Ramm, 1970). The teeth to be examined could be either sectioned or whole and the area of translucent dentine was measured and expressed as a ratio to the entire root length. A regression coefficient was derived for each tooth in the dentition, with the incisors providing the highest correlation. These results showed an error up to ±9.2 – 10.5 years at the 65% confidence interval. These results were corroborated in a recent study by Willems et al. who found an error of 9.04-11.26 years (Willems et al., 2002). Contrary to the tooth specific findings of Bang and Ramm, López-Nicolás et al. found correlation between translucency and age to be significantly higher in the canines than in the incisors (Lopez-Nicolas et al., 1996).

In 1983 Vasiliadis et al. made the important observation that apical transparency is a three dimensional phenomenon forming a butterfly pattern within the root structure (Vasiliadis et al., 1983). As the current practice was to take measurements of the area in a two dimensional section, they suggested it would be more accurate to take measurements on consecutive serial sections. Thus building up a three dimensional image of the area. Sognnaes took this a step further suggesting the use of biomedical computer imaging equipment to accurately estimate the amount of transparent dentine in three dimensions (Sognnaes et al., 1985). Other studies have used similar technology to estimate the extent of transparency in tooth sections (Drusini et al., 1991; Lopez-Nicolas et al., 1990). These studies have reported errors far less than those using subjective analysis (45% of sample had an error of ±5 years), but the equipment is highly sophisticated requiring some training and is very expensive. From his research Drusini has highlighted the main problems encountered with these methods based on sectioned teeth: it is destructive; bucco-lingual sections do not accurately reflect the full extent of the translucent zone; and the morphology of multi-rooted teeth makes appropriate sections hard to take.

A study by Solheim and Sundes in 1980 compared a number of different methods of age assessment being that of Miles, Johanson, Bang and Ramm and Dalitz – all being derived from the Gustafson method (Solheim and Sundnes, 1980). They found: that the Johanson method gave the best correlation with age when using sectioned teeth, that the Dalitz method was susceptible to a high degree of inter-examiner variability and therefore unreliable, that the Miles method was more accurate in the under 40 age group than was the method of Bang and Ramm but in the over 50 age group the reverse was true, and that overall the Bang and Ramm method was the least reliable of those tested, significantly over-estimating age. These findings are consistent with the reported results of a number other studies (Lorentsen and Solheim, 1989; Lunt, 1977; Solheim, 1989; Soomer et al., 2003). This later study, by Soomer et al., had one significant finding in addition to the others – the most accurate of the methods was that of Bang and Ramm, but only if used on sectioned teeth; on whole teeth the method was the least reliable. Finally, a study by Whittaker and Bakri found significant variation in the correlation of translucency to age between differing racial groups. They concluded that when using root translucency to estimate age racial origin should be considered and that population specific standards should be developed (Whittaker and Bakri, 1996).

5.1.8 Tooth Wear

Dental attrition, sometimes referred to as occlusal wear, is yet another of the Gustafson criteria that has been adapted and used singularly in the estimation of age. The first to adapt the criteria was Miles who developed a method that could be used within any given population as it established a baseline from within that sample (Miles, 1963a). Miles hypothesized that dental wear is continuous throughout the functional life of the tooth; wear on all three permanent molars occurs at comparable rates through similar states and patterns; and that both wear and diet are effectively uniform throughout a given population. The technique requires the use of twenty juveniles (aged between 6 and 19 years) from within the sample to establish a baseline of wear patterns and hence act as control for the whole sample. This negates the problems associated with differing wear rates in different populations. The amount of wear can then be assessed and an age estimation be made on the basis of a comparison to the baseline. In 1965, Brothwell simplified the Miles method by basing the assessment of the extent of the wear on patterns of dentine islands remaining on the occlusal surface (Brothwell, 1965).

The assumptions on which Miles based his method have, over time, been shown to be incorrect (Molnar, 1970; Nowell, 1978). These other studies have highlighted some of the problems with those assumptions, namely, that there is no consistent wear rate within a given population due to individual habits and occupational variations, different chewing patterns and variations in diet and food preparation. Other observations included the fact that variations in tooth composition that may be due to genetic or environmental factors will significantly affect the wear rates of an individual. Molnar attempted to overcome some of these difficulties by including another parameter in the assessment, that of the angle of the plane of wear. Although this was more intended to facilitate cross-cultural comparisons from an archaeological perspective, with further research it may have application in the forensic area (Molnar, 1970).

Studies that are more recent have reported varying results. Santini used the Miles/Brothwell technique and found it to be 'so imprecise as to be of little predictive value' in the estimation of age (Santini et al., 1990). A new scoring system developed by Kim et al. produced results of age estimates with an error of only ±5 years in about 60% of cases (Kim et al., 2000). Other studies have found the criteria to be more useful when used in conjunction with other criteria such as in the Johanson, Dalitz, or Gustafson methods (Solheim, 1988a). A modification by Takei attempted to take into account the incidence of restorations and wear on those teeth whose occlusal surface was covered by a restoration and therefore not subject to dentine wear patterns (Takei, 1984). Takei reported a correlation coefficient of 0.81 and that while 52% of his sample had a prediction error of ±5 years, this rose to 80% when the error was ±10 years.

Although most studies have centred on occlusal attrition, one study looked at proximal attrition (Whittaker et al., 1987). Poundbury looked at approximal attrition and found that, like occlusal attrition, it is a process that continues throughout life. Further, he found that this attrition could be classified into three types, based on the shape of the proximal surfaces. The first type was convex but reduced in dimension from what originally existed at eruption; the second was a flat contact; and the third was a concave contact. These changes are obviously degrees of severity of approximal wear but they have yet to be quantified.

5.1.9 Secondary Dentine Apposition

Secondary dentine is that which is laid down after the crown has fully formed. This occurs on the walls of the pulp chamber and is ongoing throughout life. Measures of the amounts of secondary dentine present can give an indication of the time that has elapsed since the tooth was formed and hence provide an estimation of chronological age. The different techniques used in this method vary in both the way in which the amount of secondary dentine is quantified and in the way the measurements are used to estimate age. Studies have used the ratio of pulp diameter to crown diameter (Moore, 1970), the ratio of enamel area to the area of the coronal pulp cavity (Ito, 1975), and the absolute width and height of the pulp chamber as a correlate to age (Prapanpoch, 1992), all with little or no success. Other studies have used various measurements expressed as ratios and used in multiple regression with other criteria, such as the Johanson method, resulting in an increased correlation with age (Solheim, 1992a). Others have used up to six different ratios of varying pulp chamber and tooth size measurements (Kvaal et al., 1995), which gave a significant, although weak, correlation. Cameriere et al. investigated the ratio of pulp area to entire tooth area to age and found a significant correlation with R-square=0.85 and an error of about ± 10 years at the 95% confidence level (Cameriere et al., 2004).

A validation study of the Kvaal method found a mean error of 0.5-2.5 years for age estimates with an associated standard deviation of up to 9.8 years, and that significant levels of inter- and intra-observer errors existed (Willems et al., 2002). Similar results have been reported by Soomer (Soomer et al., 2003). In all of these studies there is a need for the teeth to be in normal function and with no pathology present for any degree of accuracy to be obtained. An important observation from these studies was that the rate of secondary dentine formation slowed with an increase in age. A number of studies by Drusini et al. reproducing an earlier study by Ikeda (Ikeda et al., 1985), showed a definite correlation between decreasing pulp cavity size and age (Drusini, 1993; Drusini, 1997). The researchers derived regression formulas that gave an error of ±5 years in 81.4% of males and only slightly less for the females tested.

5.1.10 Periodontosis

Another of the Gustafson criteria was that of periodontosis which has been, as with all his other criteria, the subject of extensive investigations. The original assumption was that alveolar crest height lessened over time and that this could be used to estimate age if the amount of the change could be measured. The problem with this assumption is that it is a far more complex a system than first thought. Changes in alveolar crest height may be attributed to ageing but also to chronic periodontal disease. It has been suggested that as teeth wear occlusally they continue to erupt, causing a relative movement between the cemento-enamel junction and the height of the alveolar crest (Picton, 1957; Whittaker, 1992). Although this is a continuous process, it has been shown earlier that the tooth wear (being the process that limits this eruption) is fairly unpredictable which in turn makes the alveolar crest height changes unpredictable too. When combined with the sporadic progress of chronic periodontal disease, a very unpredictable system exists. This view has been confirmed in a study by Solheim (Solheim, 1992b), who found that although a weak correlation did exist between alveolar bone height and age, it was not strong enough to use on its own.

5.1.11 Other Methods

There are many other methods that have been proposed and these will continue to be trialled, but until supported by further research they should still be considered with some degree of caution:

i) Tooth Colour. This is based on the observation that teeth darken with age. Solheim used reflection spectrophotometry to analyse changes in root dentine colour (Solheim, 1988b). He found that, although the colour was affected by pathology and post-mortem changes (as seen in the phenomenon of pink teeth), a correlation did exist between the colour changes and age in the anterior teeth. This correlation was stronger than some reported methods but not as strong as that found with others such as the Johanson method.

ii) Peritubular Dentine Changes. Although these changes are intimately related to dentine transparency, the methods here have been included under a separate heading as they are not measuring the actual transparency, but measuring the underlying cause. A scanning electron microscope was used to assess the number of dentinal tubules and variations in their volume (and hence sclerosis) with age for a given area (Kvaal and Solheim, 1994b). No significant relationship was found between the occluded number of tubules and age. A weak correlation was found between peritubular dentine thickness and age but was not strong enough to use for forensic or archaeological estimations. A more recent study by Amariti et al. reported a stronger correlation (r=0.72 to r=0.85 for differing teeth) and a prediction error of just 8 years (Amariti et al., 2000). A different technique was used by Kosa et al. who chose to assess the degree of sclerosis by analysing the calcium and phosphorus weight ratio of the peritubular dentine. A strong correlation was found to age (r=-0.90) but no prediction errors were derived (Kosa, 1990).

iii) Surface Roughness. A study by Solheim attempted to find a correlation between an assessment of the surface structure of the tooth root, the Gustafson criteria of root resorption and age (Solheim and Kvall, 1993). Significant correlations were found, but these were not sufficiently reproducible because the assessment criteria were too subjective.

iv) Telomere Shortening. Telomeres are specialized structures located at the ends of all human chromosomes. They are a repeating sequence of 6 bases. As cells replicate and divide the full length of each telomere is not reproduced. This shortening of the telomere during the ageing process was the subject of a study by Takasaki et al. (Takasaki et al., 2003). In examining DNA extracted from dental pulp, the authors found a significant correlation between telomere length and age (R-square= 0.56). They also reported that the predictions made based on the regression of their data provided an error of ±7.5 years at the 95% confidence level. While this technique is very new, the strength of the correlation and prediction errors require the technique be refined and further validated if it is to become more widely accepted.

5.2 THE SKELETON AND THE ESTIMATION OF AGE

The fully developed human adult skeleton has 206 bones. The genesis, growth and degradational changes in these bones throughout life can be used to estimate the age of the individual. Much like dental development, many of these changes occur in an observable consistent sequence during a reasonably definite time period in the development of the human body; that is to say, the changes are age related, and common to most human beings. It is these properties that allow us to use these changes to estimate the age of an individual.

Each bone undergoes different observable changes throughout life. If we are to make use of these changes to estimate age, it is a necessary property of them that they have distinct phases that are readily identifiable. They must also occur during a limited and distinct time frame common to most humans.

It would be an over simplification to state that these changes occur at specific times. As there are no normal values for biological growth and development, an age range may be used to demarcate the points in time between which the particular bony change being observed is likely to occur for a given percentage of the population. Some authors cite the age of first appearance of the change, while others may cite the latest age at which it has appeared. Some may give an average age, such as the 50th percentile, while others use the age of total appearance (i.e. the 100th percentile). Krogman has suggested the 80th percentile is an acceptable standard to use (Krogman and Iscan, 1986).

In this section, the methods used to estimate the age of an individual will be explained. In the younger years, age estimations tend to be based on developmental processes, whereas in the older years, degradive changes are relied upon and it is these methods that are generally less accurate. (Reichs, 1986b). After initially looking at the process underlying skeletal development, those developmental changes that occur during growth of both the cranial and post-cranial skeleton will be examined, along with an analysis of their usefulness in age estimation. Finally, the degradive changes that occur after the bones have fully developed will be explored, as they too, can provide much information about the age of an individual.

5.2.1 Skeletal Development and Bone Growth

Most bones in the human body develop by first being formed in cartilage which then ossifies, that is to say they are of endochondral origin. This is a similar process to that which occurs in the developing dentition, in that a soft tissue precursor with the same approximate shape of the final product is first formed, and then calcified. With bones however, there is an exception, being the intramembranous bones of the skull.

The ossification of the bones is a continual process throughout life, with the continual remodelling of bones through osteoclastic and osteoblastic activity. With the development of the individual the bone grows in size and is constantly being remodelled. Long bones, for example, have three main loci of growth; the shaft (or diaphysis), and one at each end (the epiphyses). Separating the epiphyses from the diaphysis is a plate of hyaline cartilage. It is here that the actual growth in length of the bone occurs. Eventually the epiphyses fuse to the diaphysis and growth ceases. Beyond this point, remodelling of the bone and age related degradive changes continue to occur (White, 1991).

5.2.1.1 Post-Cranial Skeleton

a) Appearance of Centres of Ossification

At birth, there are only six epiphysial centres of ossification present. From birth until about 15 years, centres of ossification continue to appear at predictable intervals. Francis et al. summarised these timings which are reproduced, in part, in Figure 5.1 below (Francis, 1939).

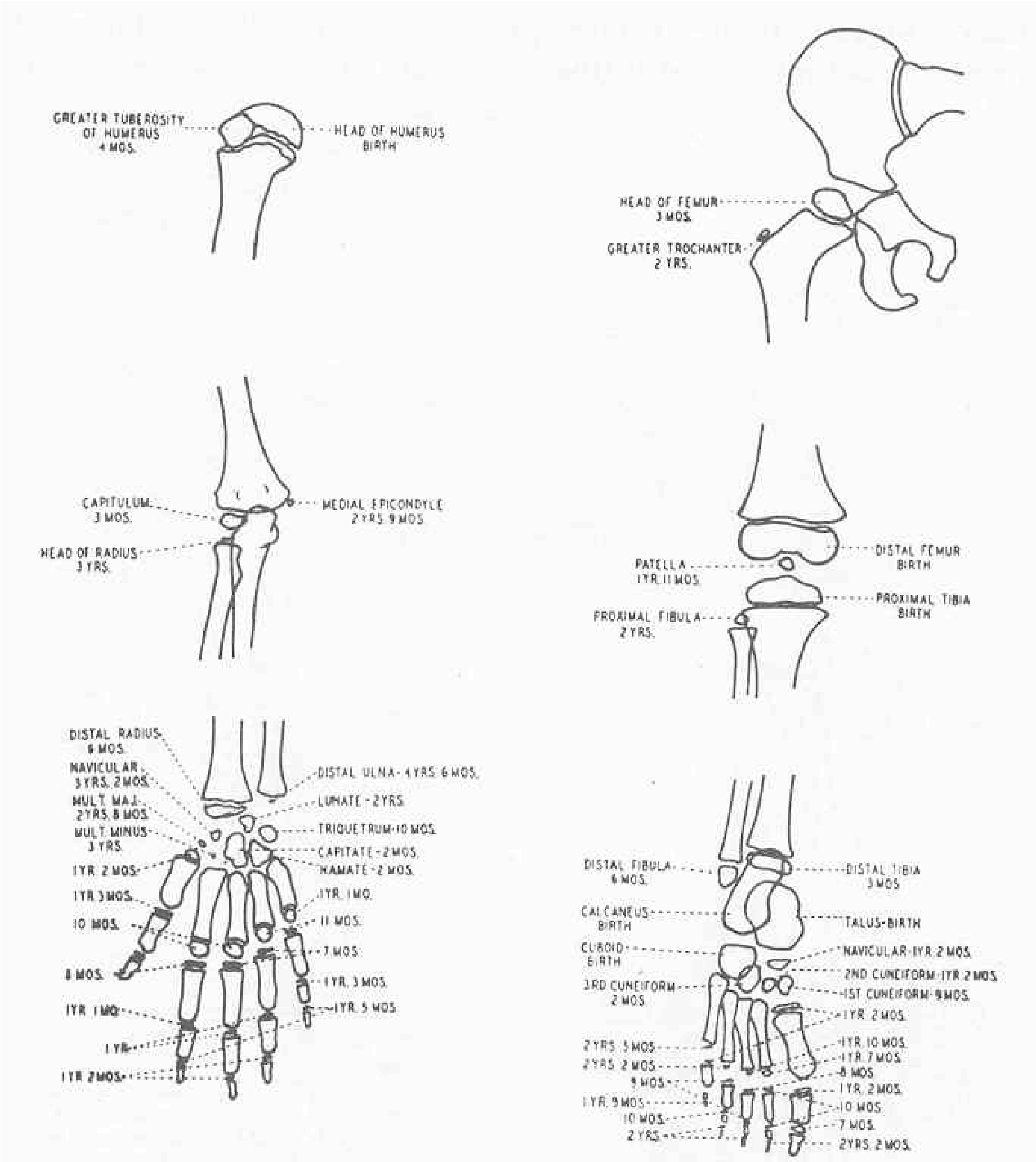


Figure 5.1: Dates of appearance of centres of ossification to 5 years-of-age in White females (from Francis et al., '39).

The sequence of events begins with the appearance of the first six centres being present at birth (calcaneus, talus, proximal femur, proximal tibia, cuboid and head of humerus), then proceeds through to the appearance of the last centre, the medial epiphysis of the clavicle at about 15 years in males and

14.5 years in females. These figures can be used to estimate age, as they represent approximately the 80th percentile, which is an appropriate standard or norm (Krogman and Iscan, 1986). In doing so, caution should be exercised, as great variability exists within humans (Flecker, 1942).

b) Linear Growth of Long Bones

The method of age estimation for juveniles based on the measured length of specific long bones is one that has been used cautiously. It is a method that suffers from inaccuracy due to the wide variation seen in absolute growth in any sample population. There is also quite wide interracial variation and as such, population specific tables should be used if available when utilizing this method. Krogman and Iscan have recommended this method be used in conjunction with other more reliable methods such as epiphysial appearance or union (Krogman and Iscan, 1986). A study by Hoffman found that absolute measurements of femur length used as a method of age estimation were no less accurate than estimations made on tooth eruption (Hoffman, 1979). It appears that the results of the study were used by the author as support for the method based upon the absolute length method. However, as has been highlighted previously in this treatise, tooth eruption is a highly variable and at times quite poor indicator of chronological age. In highlighting the similarity in the accuracy of the two methods Hoffman merely emphasised just how unreliable, as a stand alone method, length measurements can be.

c) Epiphysial Union

There have been many studies on the timing of the fusion of the various epiphyses to their respective diaphyses. Most of these studies classify the fusion according to its extent (i.e. non-, partial and complete union) when assessed either radiographically or physically. The results of these studies are very useful when estimating age.

The earliest and most widely recognised of these studies was undertaken by Stevenson (Stevenson, 1924). He classified the fusion of the epiphyses as one of either non-union, beginning union, recent union or complete union. As with most growth related methods these stages were chosen as they were seen to be discrete and observable. Many studies have followed, some using similar classifications (Krogman, 1955; Stewart, 1954; Todd, 1930b), while others came up with new methods of classification, such as including more stages (McKern and Stewart, 1957). It is generally agreed that direct observation of the bone in question is a far superior method to examination of a radiograph of the same area (Krogman and Iscan, 1986). The exceptions to this are that of the hand and knee. If skeletonised, the hand in particular, will normally have lost most of its epiphyses. However, these two areas, if intact, can be readily assessed using a comparison to a radiographic atlas of the developing part -- see Greulich and Pyle for their atlas of the hand (Greulich and Pyle, 1959) and Pyle and Hoerr for their atlas of the knee (Pyle and Hoerr, 1969).

While there may be differences of opinion on the actual ages at which specific unions occur, the overall sequence is generally agreed upon as being standard for Homo sapiens. The timing of the union of the various epiphyses and diaphyses is subject to a degree of variability. Krogman recommended using tables derived form the Hamann-Todd Collection, used in the study by Johnston, supplementing any estimations with reference to tables based on American war dead derived from the study by Stewart in 1954 (Krogman and Iscan, 1986; Stewart, 1954).

These methods cover the age range from approximately 11.5 years with the beginning of the union of the acetabulum to ‘26 years plus’ for the union of the medial epiphysis of the clavicle.

5.2.1.2 Cranial Skeleton

The development of the bones of the skull along with the closure of the cranial sutures provide further means of estimating age. While the growth of the cranial bones occurs during the early years of development - an area well covered by other methods of age estimation - it is the closure of the cranial sutures that covers a far larger age range.

a) Cranial Bone Growth

A number of studies have been undertaken to examine the timing of cranial bone growth to be used to estimate chronological age. One such study by Weaver examined the development of the temporal bones by dividing the growth of the bone into six discrete stages. He concluded that as the tympanic plate was fully formed, according to his stages, by age 2.5 years that this method was useful for ages up to this point (Weaver, 1979).

A study by Redfield examined the development of the occipital bone (Redfield, 1970). By observing the fusion of the four separate pieces of the developing bone, an estimate of age could be made. As the fusion of the bone was complete by about 7 years, this provided the upper limit of comparison for this technique.

b) Cranial Suture Closure

As the bones of the cranial vault develop, they eventually meet with each adjoining bone and fuse. The region where the fusion occurs is known as a suture and it is the timing of the closure of this suture that results in fusion of the cranial bones that can also be used to estimate age. Owing to the thickness of the cranial bones there is a difference in the timing of the closure of any of the sutures between their inner (endocranial) and outer (ectocranial) aspects. Studies on the timings of the commencement and completion of both endo- and ectocranial suture closure have yielded varying results (McKern and Stewart, 1957; Powers, 1962; Singer, 1953). It is generally accepted that while the timings of the commencement of both endo- and ectocranial sutures are similar, the fact that ectocranial sutures often fail to completely fuse means that the endocranial timings are a more reliable indicator of age (Todd and Lyon Jr., 1924).

The three sutures used in this technique (pictured below in Figure 5.2) have been divided into a number of regions as they frequently do not fuse along the entire length of the suture simultaneously.

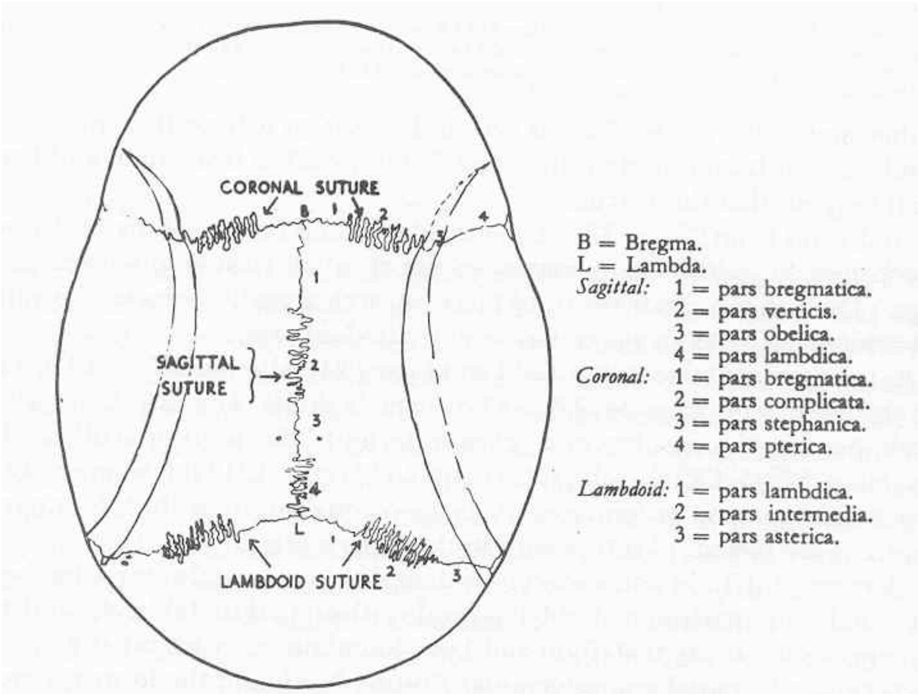


Figure 5.2: Diagrammatic representation of the subdivisions of the cranial vault sutures (from McKern and Stewart, '57).

The tables used in this technique provide figures for the onset and completion of suture closure in all these regions and covers, the age range of approximately 17 to 50 years.

The metopic suture that exists between the right and left halves of the frontal bone at birth is usually closed by about 2 years-of-age. It can however persist in some individuals into adult life. This feature occurs in about 10% of Caucasoids and Mongoloids but only in about 2% of Negroids (Montagu, 1938; Woo, 1949).

The spheno-occipital synchondrosis, although not a suture of the cranial vault, is one of the sutures of the occipital bone. Commonly known as the basilar suture, various studies have placed its fusion between 20 and 29 years-of-age (Redfield, 1970). The Krogman study found that 95% of basilar sutures were united between 20 and 25 years-of-age (Krogman and Iscan, 1986). It is these figures that are today used as a general guideline.

Recently, however, Meindl et al., suggested that the ectocranial closure patterns, especially those in the anterior lateral sutures may accurately reflect changes in the adult years (Meindl et al., 1985). Generally speaking the accuracy of the method of age estimation based on suture closure timings is limited. Cobb recommended that, in using the Todd and Lyon tables, an error of ±9 years should given (Cobb, 1952). As such this method, like many others, may give a rough indication of the chronological age of an individual, but is best used in conjunction with, or to corroborate, other methods.

5.2.2 Degradive Changes

The age related changes that occur in bones following their complete formation are the basis for a number of current methods of ageing the adult skeleton. The changes are the result of both osteoclastic and osteoblastic activity that cause observable and measurable morphological changes to the bony surfaces. They are more obvious in certain bones and for this reason studies have been undertaken on bones that consistently show the greatest changes over time. While most of these methods involve direct macroscopic comparison to photographs or casts of the particular bone at known ages, some involve radiographic or histological examination.

a) Scapula

A study by Graves in 1922 listed what he termed 'post-maturity ossification and atrophic' changes of the scapula (Graves, 1922). While the epiphysial union in this bone is complete by about 25 years-of-age, it is these further changes that are useful in age estimation after this point. The changes themselves involve the lipping and faceting of certain areas, appearance of christae scapulae, appearance of surface and deep vascularity, localized areas of atrophy, and buckling and distortion of the infraspinous region. These changes generally begin between 30 and 50 years, each type of change first appearing within a specific 5 year range in during this period.

b) Ribs

The age related changes of the sternal end of the ribs, at the costochondral junction, have been extensively investigated. Examination of this region can be particularly useful. While epiphysial union of the ribs commences as early as 17 years and is generally complete by 24 years-of-age, (ribs 4-9 completing last) the ongoing age related changes take place over an extended period covering from about 16 to 70 years. A number of studies by Iscan and Loth have produced tables that describe in detail the changes that may be observed over this time (Iscan and Loth, 1984; Iscan and Loth, 1986; Iscan et al., 1985). The changes have been divided into eight distinct phases that do differ slightly between male and female. A detailed description and a series of photographs of the expected changes in each phase make identification of the phase and the resultant age estimation possible.

c) Vertebral Column

Comparatively fewer studies have been carried out in this area. The most notable of the changes that occur are osteophytic, that is, the lipping at the periphery of the articular surfaces. It was these changes that were the subject of a study by Stewart (Stewart, 1958). He found that generally lipping did not occur under about 30 years-of-age and that extensive lipping usually only occurred in those over 40. He concluded, however, that this method was not a very reliable one.

d) Pelvis – The Pubic Symphysis

The right and left pubic bones meet in the midline at the pubic symphysis. The articular or symphyseal surfaces of these bones undergo morphological changes that are age related. Many studies have been undertaken to investigate what has become one of the most reliable skeletal methods of age estimation. Most of these studies have been based on the initial work done by Todd in a number of studies carried out in the 1920s (Todd, 1920; Todd, 1921a; Todd, 1921b). By dividing the age related changes he observed into ten distinct phases Todd described in detail the morphological changes that occurred at the symphyseal surface over the age range of 18 to 50 years. Below, in Figure 5.3, is a diagram of these ten phases. A detailed description of each was given by Todd to assist in the identification of each phase.

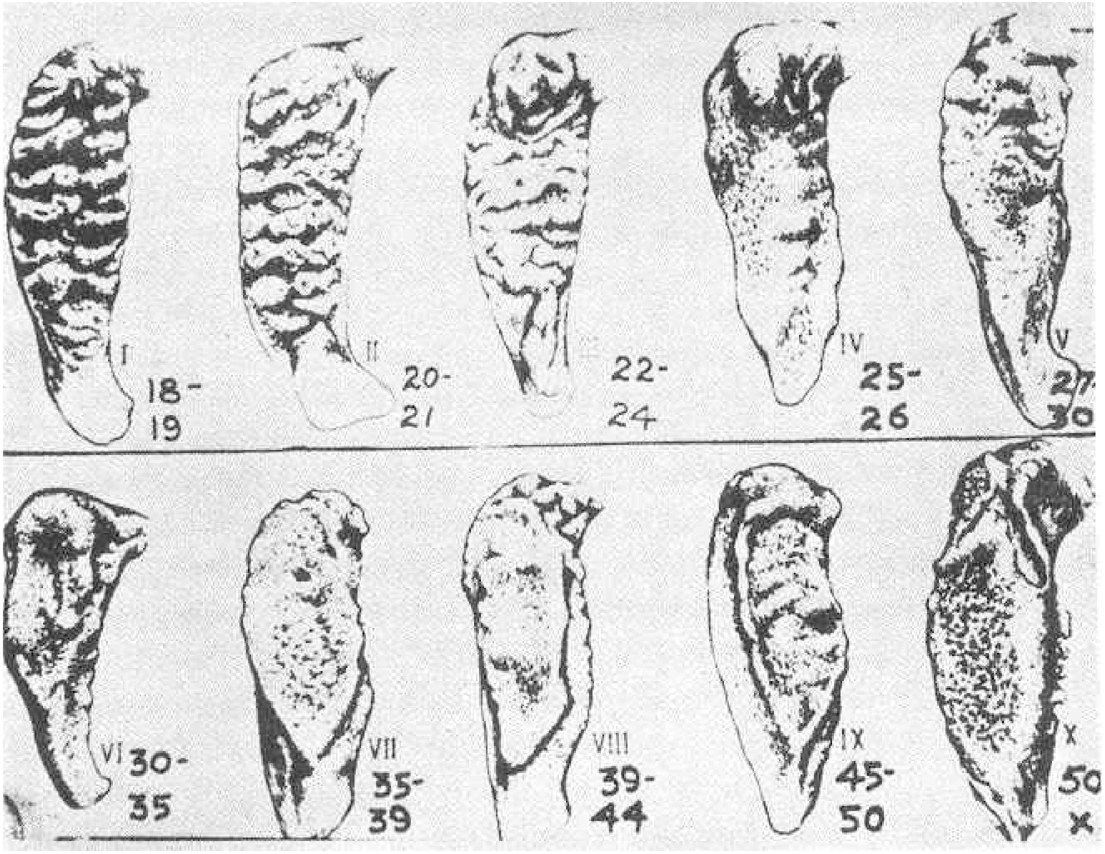


Figure 5.3 Model standards of Todd's 10 typical phases (from McKern and Stewart '57).

Todd concluded that this technique was more accurate in the earlier years (20-40) and should be used with caution, allowing an error of ±5 years if used as the sole source of age estimation.

A radiographic comparison technique involving 4 distinct phases covering the range 25-55 years was later suggested by Todd (Todd, 1930a), although this was not as accurate as the previous method.

McKern and Stewart devised a technique based upon the phases of the Todd system but where the symphyseal surface was divided into three separate areas; the dorsal plateau, the ventral rampart and the symphyseal rim

(McKern and Stewart, 1957). In this component analysis, each of these areas was to be analysed separately and classified into one of five age specific phases. The number of phases had been condensed from Todd's original ten down to five. Each phase was given a score and the three separate scores totalled to give a final score that was converted to an estimate of chronological age based upon tables produced by the authors. Figure 5.4 below depicts these phases.

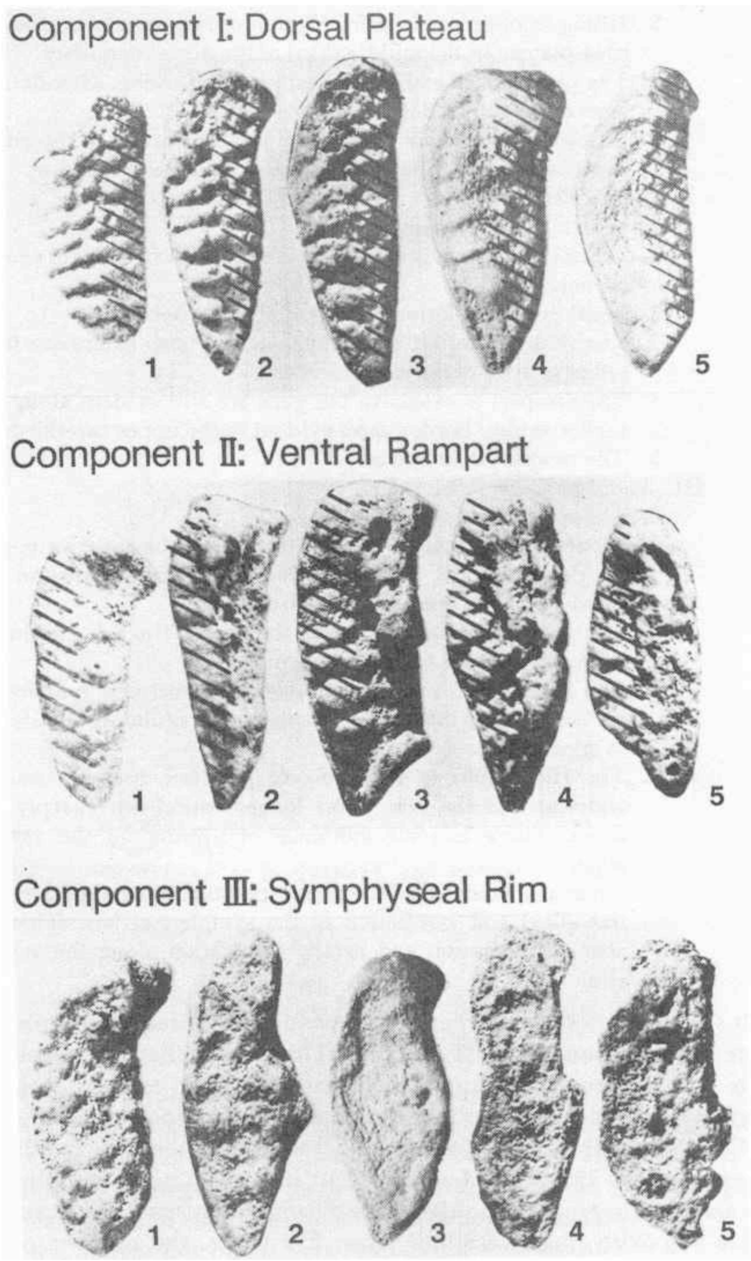


Figure 5.4: Component analysis of the pubic symphysis in males (from McKern and Stewart '57).

It has been found that the work of Todd, being based on male standards, is less accurate when applied to the female pelvis. For this reason McKern and Gilbert formulated a further set of standards for the female pelvis based upon the same three component, five phase system (Gilbert and McKern, 1973).

A study by Suchey in 1979 focused on the problems associated with these two well known and widely used systems (Suchey, 1979). Suchey found that the Todd system tended to overage male specimens and the McKern and Stewart system tended to underestimate overall variability. These results supported similar claims made in a later study by Meindl et al. (Meindl et al., 1985). These systemic errors were attributed to the small sample sizes on which the systems were originally developed. Suchey then proposed modifications to the two systems to negate these shortcomings – the ten stages of the Todd system were collapsed in to five with modified limits; and the McKern and Stewart combined sum approach was restructured into one of pattern analysis, again with modification of age ranges (Suchey et al., 1986). Later, Suchey and Brooks further modified this system to a series of six phases represented by an 'early' and 'late' pattern to mark the end points of each phase (Brooks and Suchey, 1990).

Today it is common to use this method of age estimation using the Suchey-Brooks system based upon the work of both Todd, and McKern and Stewart. Casts of the features are available and make the analysis of the phases far more consistent and therefore more accurate.

e) Pelvis – The Auricular Surface

Like the pubic symphysis the sacroiliac articular surface of the pelvis, or auricular surface as it is commonly known, undergoes common age related morphological changes that are reasonably consistent across the species in the timing of their appearance. As with the pubic symphysis, casts are available of the region and are based upon the changes that would be generally be observed in the majority of the population at each phase. There are eight phases, a detailed description of which is available and is based upon the work of Lovejoy et al. (Lovejoy et al., 1985b). Unlike the pubic symphysis however, there is no sexual dimorphism in the morphology or timing of the appearance of these features. The phase descriptions and models cover the age range 20-60 and should both be referred to when using this technique.

5.2.3 Radiographic Methods

Radiographically observable changes to the macroscopic structure of the bone provide yet another avenue for age estimation. Changes such as the process of epiphysial fusion, morphological changes to the cancellous and medullary bone and to the size of the medullary cavity have all been studied in an attempt to find common, observable and age consistent features. A study by Schranz tabled the changes that may be observed radiographically in the proximal end of the humerus between the ages of 15 and 75+ years (Schranz, 1959). Building on this work Nemeskeri divided the changes into a series of six phases and described a similar set of phases for the proximal end of the femur (Nemeskéri et al., 1960). Figure 5.5 below depicts the six phases described by Nemeskeri. When used in conjunction with the detailed descriptions this method can be used to estimate age within the ranges defined by Schranz.

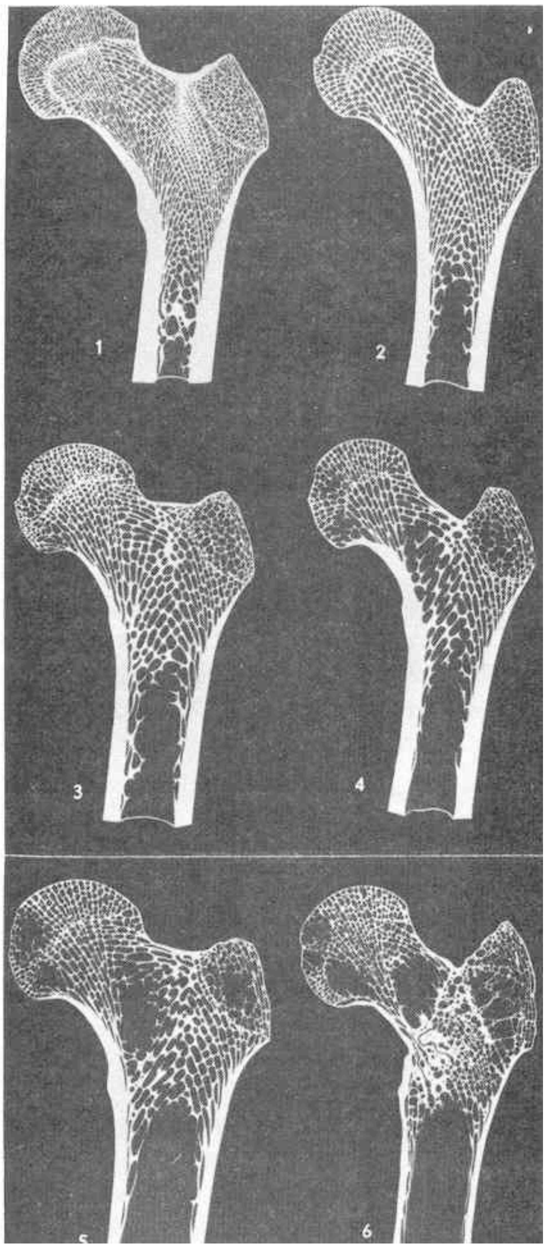


Figure 5.5: Phases of structural change in the cancellous bone of the proximal epiphysis of the femur (from Ascádi and Nemeskeri, 70) .

5.2.4 Histological Methods

These methods have predominantly been based upon the microscopic changes that occur within the cortex of long bones. A number of studies attempted to estimate age based upon the number of observable microstructures within the field of view as seen through a conventional microscope (Burr and Peotrowski, 1982; Kerley, 1965; Singh and Gundberg, 1970). These structures were whole osteons, fragmentary osteons, circumferential lamellar bone and Haversian canals. The total number of these specific structures was said to be related to age, but methodological problems such as the great variation in field size between individual microscopes severely affected the reproducibility of results. The age range covered was between 18 and 76 years with a maximum reported error of ±5 years. A further study by Thompson and Gunness-Hey found these histological methods far less accurate than other morphological methods (Thompson and Gunness-Hey, 1981).

Many studies have been undertaken in an attempt to find the most effective and reliable method of age estimation. Some have sought to combine a number of specific methods, such as epiphysial fusion and dental eruption. Others have sought to discover the most effective combination of techniques (Lovejoy et al., 1985a; Meindl et al., 1983). Some of the methods reviewed above require specialized equipment and training which, if available, can yield quite satisfactory results. As with any of the methods outlined above, the most effective and accurate method is often a combination of many methods used in support of each other. This is a common finding, most recently supported by a study undertaken to examine the accuracy of the multifaceted approach to forensic age estimation undertaken on living persons at the Institute of Legal Medicine in Berlin (Schmeling et al., 2003). Over a period of eight years up to the year 2000, 45 verifiable cases of age estimation were undertaken using a combination of dental and anthropological methods. In 41 of the 45 cases the deviation between estimated and true age was less than ±12 months.

Age estimation based upon any of these methods, either singularly or in combination, often proves quite accurate. In cases where only one method can be used, it is the use of calcification timings in teeth that has been shown to provide a more accurate estimation when compared to other available techniques. It is the methods based upon dental development that will be investigated in the next section.

Chapter 6

Tooth Development and Age Estimation

There are many different methods based on both skeletal and dental observations for estimating age at death. The most widely used of these have been described in the previous chapter and, as was shown, the accuracy of these methods varies greatly. To date the most accurate methods of age estimation for juveniles and young adults have used the assessment of dental age based on tooth development.

It is the aim of this chapter to look at tooth development in depth. The chronology of tooth development as well as factors affecting the rate of development will be examined. The various methods of age estimation that involve some form of assessment of the degree of tooth development will be investigated. The system devised by Demirjian, Goldstein and Tanner (Demirjian et al., 1973), will be examined at length, being the original work that this current Sydney study is based on.

Dental development is itself a broad term. Ciapparelli stated that data concerning 'dental development' could, and have, been based upon examination of any or all of the following areas:

- histological premineralization sequences,
- histological mineralization sequences,
- incremental patterns of enamel and dentine formation,

- emergence of teeth into the oral cavity and
- gross mineralization sequences observed by either radiographic means or by direct observation of dissected developing teeth in situ or individually (Ciapparelli, 1992).

While the first two areas were mentioned briefly in the previous chapter it is not intended to investigate age assessment techniques based upon examination of histological sections here. Also in the previous chapter techniques for age assessment based on both incremental line patterns and tooth emergence were covered. It is the area of examination of gross mineralization sequences that is the main subject of this chapter and indeed, of this research project.

It has been established by many researchers that analysis of dental development provides the most accurate methods of age estimation (Garn et al., 1959; Liliequist and Lundberg, 1971; Stewart, 1963). Given that the age range to which these techniques may be applied is limited, they are extremely useful in the appropriate cases. The reasons for this include:

- the relative indestructibility of the teeth peri- and post-mortem when compared with other tissue systems,
- with the decreasing prevalence of dental caries and the consequential decrease in the incidence of restorative dental treatment it is becoming more uncommon to identify individuals based on the comparison of any pre-existing dental treatment.

In light of the latter point, the reconstructive approach to the identification may be required. In such circumstances a physically descriptive profile of the child is developed, of which the age estimation based on tooth development may well be the most accurate aspect. An important complicating factor in this process is that depending on the age at which the ante-mortem radiographs were taken, major changes in the developing dentition of the child may have taken place up to the time of their death. With this in mind there may be few, if any, points for comparison between the ante- and post-mortem radiographs, and as such the case may then require a reconstructive approach as previously mentioned. Of all the systems used to examine growth and estimate age, dental development is the one system least likely to be affected by environmental influences, and therefore provides the most predictable and consistent basis for age estimation.

The reasons for the accuracy of these methods are many, but they are based on two important principles. Firstly, the mineralization sequences of all the teeth are well established, and a number of different systems of age assessment have been based upon them. This sequence will be expanded upon in the next section. Secondly, the rates at which the mineralization occurs are influenced minimally by extrinsic factors and are relatively constant for a given population. It is the factors that do affect the timing and rate of mineralization that will be discussed in the subsequent section.

6.1 CHRONOLOGY OF TOOTH DEVELOPMENT

Up until the landmark study by Logan and Kronfeld in 1933 it was generally held that the calcification of all the permanent teeth began at the same time

(Logan and Kronfeld, 1933). This assumption was based upon tables produced 40 years earlier by Legros and Magitot in 1893 (quoted in (Logan and Kronfeld, 1933)). In fact, at the time there were a number of other studies that also incorrectly stated the timing of commencement of calcification of the teeth. Logan and Kronfeld summarised these other findings along with their own and are reproduced below in Table 6.1:

Upper Jaw — Tooth	Legros-Magitot (Reproduced by Noyes, Bödecker)	Peirce	Black	Brady	Churchill	Author's Findings
1	1st month	1st year	1st year	1st year	2 months	3 to 6 months
2	1st month	2nd year	2nd year	2nd year	2 months	1 year to 15 months
3	1st month	3rd year	3rd year	3rd year	4½ months	3 to 6 months
4	1st month	4th year	5th year	4th year	3 years	1½ to 2 years
5	1st month	5th year	5th year	4th year	4 years	2 to 2½ years
6	6th (fetal) month	25th (fetal) week	Before birth	25th (fetal) week	9th (fetal) month	1 to 4 months
7	3rd year	5th year	6th year	5th year	4 years	2 to 2½ years
8	12th year	9th year	9th year	8th year	8 years	7 to 9 years
Lower Jaw — Tooth						
1	1st month	1st year	1st year	1st year	2 months	3 to 6 months
2	1st month	2nd year	2nd year	2nd year	2 months	3 to 6 months
3	1st month	3rd year	3rd year	3rd year	4½ months	3 to 6 months
4	1st month	4th year	5th year	4th year	3 years	1½ to 2 years
5	1st month	5th year	5th year	4th year	4 years	2 to 2½ years
6	6th (fetal) month	25th (fetal) week	Before birth	25th (fetal) week	9th (fetal) month	1 to 4 months
7	3rd year	5th year	6th year	5th year	4 years	2 to 2½ years
8	12th year	9th year	9th year	8th year	8 years	7 to 9 years

Table 6.1: Time of beginning of calcification of the permanent teeth as reported by various researchers. The 'Author's findings' refer to those of Logan and Kronfeld (from Logan and Kronfeld, '33).

Today we know that the development of the dentition commences at differing stages in the growth of the child dependent on the teeth in question. It is recognised that there is a degree of variation in the actual timing due to the inherent biological variability of human beings, hence the use of ranges rather than discrete timings. Based on the earlier work of Fanning (Fanning, 1961), Moorrees, Fanning and Hunt published standards for the chronology of the formation of the deciduous (Moorrees et al., 1963c) and permanent dentition (Moorrees et al., 1963a). Relying on a sample of over 200 children, the resultant tables are more comprehensive and more statistically sound than that of Logan and Kronfeld, and are still in use today. While this study examined all of the dentition, by way of example, only the tables for the mandibular canines and premolars for females are reproduced in Figure 6.1 below.

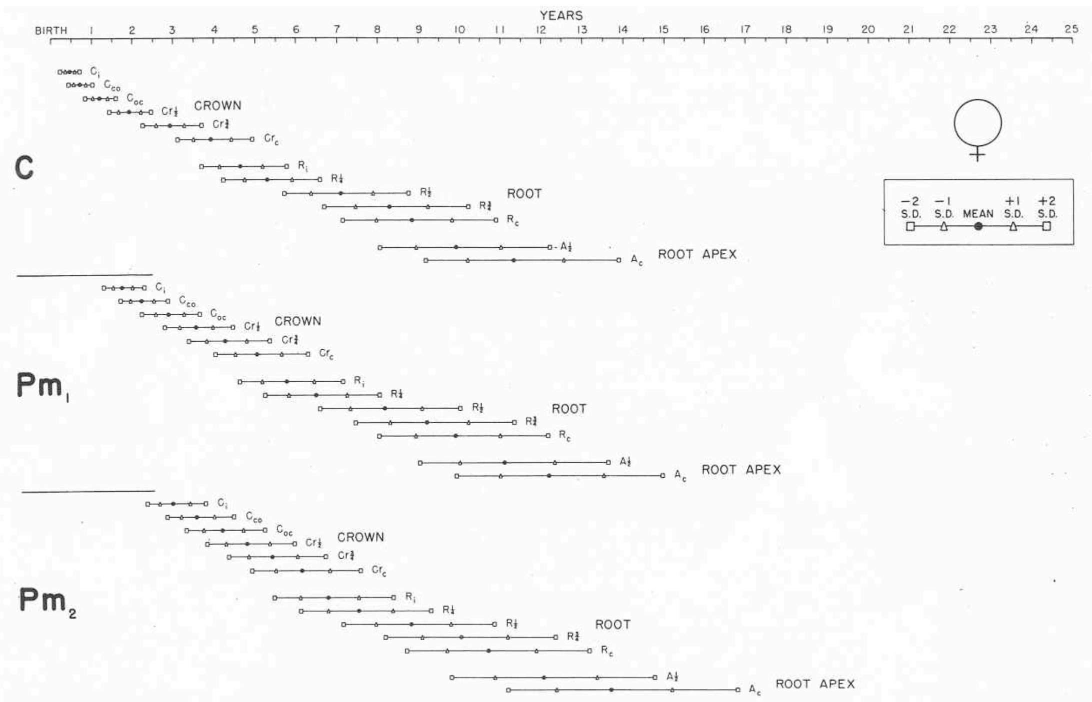


Figure 6.1: Norms of tooth formation of permanent mandibular canines, and premolars of females (from Moorrees, Fanning and Hunt, 63).

It is widely acknowledged that the teeth develop through a succession of stages that are common to all humans and that all teeth, both deciduous and permanent, normally pass through all these stages of development. These stages are predictable and observable and it is the observation of these stages that many methods of age estimation are based upon.

6.2 VARIATION IN THE TIMING AND RATE OF TOOTH DEVELOPMENT

The sequence of tooth development detailed above is reasonably consistent throughout any given population although there are some minor variations. There is, however, a greater degree of variation between individuals in both the timing of the initiation of tooth development as well as the rate at which it progresses. If the degree of dental development is to be used as an indication of chronological age, it is essential that any factors affecting the timing and rate of that development are thoroughly understood and taken into account.

As will be seen, the greatest single factor that results in variation of both timing and rate of dental development is that of genetics. Variations in age, sex, race, even population substructure have the most profound effect on dental development of all the potential influences. These factors will be examined in some detail. Further, there are many non-genetic or environmental factors that may result in minor, yet sometimes significant, alterations in the timing and rate of dental development. These factors too, will be considered in this section.

6.2.1 GENETIC FACTORS

The growth and development in the human body is the result of the interaction of genetic coding and of extra-genetic or environmental influences. The genetic information in DNA is transmitted to the offspring on the parental chromosomes contained within the ovum and sperm. This information is then retained by the new organism and is faithfully reproduced as the cells divide and the offspring grows. The information carried on the chromosomes controls the structures of all the proteins making up the new organism and regulates their synthesis and interaction with other substances. Variations between individuals in the timing and extent of their growth and development are the consequences of differences in the enzyme or protein synthesis and as such are a reflection of the genetic constitution of each individual (Roberts, 1981). As such, genes play a critical role in initiating and regulating the various stages of dental development.

There is considerable potential for variation in this regulation process. It is widely accepted that genetic control of development occurs as a result of switch mechanisms, which switch on and off the activity of particular genes at specific times in development, producing specific substances which result in a specific cellular activity (Roberts, 1981; Thesleff, 1998). Any variations in the efficiency or the timing of the initiation of these switching mechanisms may result in individual variation in growth and development, reflecting the underlying differences in the genetic constitution of the individual. It is important to note that any variations or errors occurring in the synthesis of the specific substances may also have a profound affect on development; this will be covered in a later section.

It is evident in examining the process of development of the human tooth that there is an essential time-linked differentiation of the various cell types, be they of mesodermal or ectomesenchymal origin. In all growth, communication between nearby cells constitutes a central mechanism by which advancing development is regulated. The signalling networks through which the epithelial and mesenchymal components of the developing tooth communicate during several stages of development are genetically regulated. The response of each cell to any such signal during this process is determined by ‘master regulatory genes’ among other factors (Ten Cate, 1995; Thesleff, 1998). As such the initiation and rate of differential growth by cell reproduction, and the synthesis of specific proteins represents a fundamental level of gene expression (Biggerstaff, 1979).

A specific example of this process is that of the cells of the dental papilla transforming into functional odontoblasts that then proceed to produce the dentine matrix. The cellular transformation of the papilla cells requires a change in the cells' morphology and function that must reflect the activation of specific gene complexes. The overall process is controlled by a genetic timetable. It is the extent of the influence of that genetic control that is of interest in this current section.

The timing of the initiation and rate of dental development is genetically governed to a large degree (Alvesalo, 1971; Glasstone, 1963; Ryman, 1975; Thesleff and Sharpe, 1997; Varrela, 1991). Studies have estimated the contribution of genetic control to account for anything from 78% (Hatton, 1955) to as much as 90% of the variance observed (Garn et al., 1960). A similar conclusion was reached by Pelsmaekers et al. who, in another sibling study on dizygotic twins, found the non-genetic 'specific environmental factors' contributed less than 10% to the control of dental maturation (Pelsmaekers et al., 1997). Merwin and Harris found that the genetic factors were responsible for about 84% of the variation in the rate of dental development (Merwin and Harris, 1998).

There are many studies that have found that the morphological variations in the human dentition exhibit a high degree of heritability (Biggerstaff, 1979; Garn et al., 1965b; Kraus et al., 1959; Krogman, 1967; Lasker, 1950; Moorrees, 1962; Osborne and DeGeorge, 1959; Townsend and Brown, 1978; Townsend, 1980). If this is so, and accepting the role genes also play in the timing of initiation and rate of development, it would follow that these too may well be heritable traits.

6.2.1.1 Racial Variation in Growth

Genetic variation between individuals is obviously the norm. There are however, groups that display similar trends in growth and developmental variation. These trends become obvious when examining subjects of similar genetic ancestry and as such, individuals of similar geographical and racial origins show similarities in their growth patterns. It is these trends that form the basis for many methods of odontological and anthropological age estimation methods. As such, it is often important to identify the racial background of the cases in question.

Many studies have been undertaken that use the geographical origin of the subject, expressed in terms of recent ancestry, to provide a simple classification (Demirjian et al., 1973; Eid et al., 2002; Hägg and Matsson, 1985; Nyström, 1986; Teivens, 1996; Willems et al., 2001). In this way general trends based on the race of the subject groups in the samples being studied may be made.

It would be wrong, however, to assume that any differences observed between racial groups are purely of genetic origin. As discussed earlier, growth is affected by both genetic and environmental stimuli and these environmental factors do not act independently. For example, children living in tropical areas may be subject to certain infections that do not exist in cooler latitudes. In some areas widespread infection may be the result of the interaction of climate and nutrition, such as in some developing nations. Nutrition and socio-economic status are sometimes influenced by religion and culture, which are partly determined by both geographical location and racial background. Further, genetically dissimilar populations may respond differently to the same environmental conditions (Marshall, 1981). As can be seen, it is often difficult to separate out the relative importance of genetic and environmental factors in the control of growth and development.

There have been many studies that have investigated environmental or non-genetic influences on growth. The results of these will be discussed in a later section, but it is interesting to note at this point that they predominantly highlight the far greater importance of genetic over environmental influences as the key factor in variations in dental development. Contrary to this opinion, Habicht suggested that 'any racial or ethnic effect on mean pre-school [skeletal] growth is small compared with environmental effects' (Habicht et al., 1974). This conclusion however, was found to be flawed. The data in this study did not distinguish between the effects on growth of race and socio-economic conditions. The general consensus is that populations in different parts of the world and of different racial origins do vary greatly, in not only their final adult statures' but also in their rates of maturation. Further, these variations are primarily due to genetic variation and not environmental factors (Burkitt, 1924; Eveleth and Tanner, 1976; Genovés, 1967; Marshall, 1981; Tanner, 1962; Trotter and Gleser, 1952; Trotter and Gleser, 1977).

a) Global Variability in Dental Maturation

The results of several studies do show trends in dental maturation rates that are consistent for a given racial group, but vary significantly to other groups. A study by Tompkins found that African Negroids were advanced in the timing of the development of the third molar compared to French-Canadian Caucasoids, and were also advanced over Native Americans but to a lesser degree (Tompkins, 1996). Cherktow found that dental calcification in black South African children was advanced compared to that in white South African children (Cherktow, 1980). Owsley and Jantz concluded there were population differences in the timing of tooth formation between American whites and the Arikara people (a native American population) (Owsley and Jantz, 1983). Harris and McKee found that African-Americans from the United States mid-south were advanced in dental development over mid-south European-Americans (Harris and McKee, 1990). These trends corroborated the results of an earlier study that compared the dental development as measured by degree of calcification of African-American and European-American children, only in a different area of the United States to the later study (Loevy, 1983a). As in the study by Tompkins, both American groups were advanced over the French-Canadian group. A study by Maki et al. on children living in San Francisco found that the Caucasian Americans were significantly advanced over those of Japanese and Chinese ancestry, but that the Japanese and Chinese children shared similar dental developmental rates (Maki et al., 1999).

In other parts of the world, a study by Fanning and Moorrees found a significant delay in the timing of calcification of mandibular third molars in Australian Caucasoids when compared to the Australian Aborigines (Fanning and Moorees, 1969). Liversidge found that the dental development of Caucasian children living in London (both of Anglo and Bangladeshi descent) was advanced by 0.5 years in females and 0.7 years in males compared to the French-Canadian reference sample, but did not differ significantly from each other (Liversidge et al., 1999). Davidson and Rodd found Somali children to be advanced by about one year over British children who were, in turn, advanced over the Canadian reference sample by up to 6 months (Davidson and Rodd, 2001). Frucht et al. found that when applying the standards of the Demirjian system, the dental ages of a sample of children from south-west Germany were not significantly related to those of the French-Canadian reference sample (Frucht et al., 2000). Davis and Haag, in a study on children in China, found that the local children were retarded in their dental development by a mean of 11 months for males and 7 months for females when compared to the French-Canadian reference sample, when using the age estimation method devised by Demirjian (Davis and Häag, 1994). Similarly, a study conducted on children in southern India using the Demirjian system significantly overestimated dental age by a mean of 3 years in males and 2.8 years in females (Koshy and Tandon, 1998). It was significant in this study, and common to many other similar studies, that the predicted age in the older age groups tended to have the greatest error. Williems' study of children in Belgium found their dental ages to be retarded when compared to the French-Canadian reference sample - a mean of 0.4 years for males and 0.7 years for females (Willems et al., 2001), whereas a study by Nykanen et al. on children in Norway found that their rate of dental development did not differ significantly from that of the French-Canadian reference sample (Nykanen et al., 1998). The findings of Willems were supported by similar results in a more recent Belgian study by Chaillet et al. (Chaillet et al., 2004). Nystrom found that the dental age of a sample of Finnish children was advanced by up to 7 months over the French-Canadian sample (Nyström, 1986). In a study on Brazilian children Eid found their dental age to be advanced over the French-Canadian sample by 0.68 years for males and 0.61 years for females (Eid et al., 2002). Finally, a number of studies undertaken in Sweden have reported varying but similar results in that the dental development of Swedish children lags behind that of the Canadian children by, on average, 10 months (Hägg and Matsson, 1985; Staaf et al., 1991; Teivens and Mörnstad, 2001a). Mornstaad found this difference varied from 0.4 to 1.8 years (Mörnstad, 1995). Teivens also found that Swedish dental development was advanced over that of a Korean sample by 2 months in males and 6 months in females (Teivens and Mörnstad, 2001a). More recently in Australia, a study by McKenna et al. on a sample of South Australian children aged 4.9 to 16.9 years found that estimates of dental age based on Canadian standards resulted in overestimates of up to 3.8 years below the age of 15. Beyond this age the use of these standards tended to underestimate Australian ages. The authors reported that these results indicated that South Australian children are less advanced in early years compared to the Canadian children, but more advanced in later years (McKenna et al., 2002).

Other studies have revealed that even within the same racial group within the same nation there are statistically significant varying rates of development. Nyström developed predictive tables based upon a sample from one region of Finland and applied them elsewhere in the same country (Nyström, 1988). Despite the population of Finland being considered 'fairly [racially] homogeneous' (Nyström, 1988) the author found statistically significant differences in predicted ages between samples from Northern Finland when compared to the reference sample of Helsinki, the northern sample being the more advanced. Similar variations have been observed in other countries. A study by Mappes et al. found significant differences in the rate of dental development between Caucasian children of Memphis (mid-south USA) and that of Caucasian children in Cleveland (mid-west USA) (Mappes, 1992). These variations have been found in even closer geographical locales. Loevy and Shore found that the dental development of a sample of Caucasian children from a suburb of Chicago was significantly advanced over another Caucasian sample examined from within the city of Chicago (Loevy and Shore, 1985). Not surprisingly most of these authors have concluded that population specific standards are required when using any system of age estimation based upon dental development.

The majority of these authors have suggested that the variations in rates of dental development may be due, at least in part, to racial differences between the sample populations. The above observations may well be the result of different genetic ancestry with the interbreeding of the populations being prevented, or at least restricted, by the geography of the land. While this effect may keep gene pools and consequently their various rates of development relatively different and separate, it is this genetic heritage that is responsible for these differences in the first place. This is an observation supported by studies of seventeen African populations that have shown stature is more closely related to tribal origin than to geographical location (Eveleth and Tanner, 1976).

It was interesting to note the observation by Nyström that Finland has a 'fairly homogeneous' population (Nyström, 1988). The concept of racially homogenous populations is an extremely relative one. Indeed the concept of race today 'is a rather ill defined notion,' as both folk and legal definitions of racial groupings reflect little if any biological reality (Reichs, 1986a). Even noted anthropologists Krogman and Stewart advise caution in attempting to classify skeletal remains as members of specific racial groups (Krogman and Iscan, 1986; Stewart, 1979). The reason for these observations is that it is unlikely that any populations are 'pure' or unmixed (St Hoyme and Iscan, 1989).

While gene pools may have remained relatively isolated over a number of generations, the populations of the earth have always migrated. The Babylonians systematically repopulated conquered countries, as did the Romans. The Israelites migrated to Egypt 4000 years ago, while Germans migrated to the Ukraine and Koreans to Central Asia during the 19th century – all in the aftermath of famine. During the Bronze Age, Mediterranean traders visited England and Ireland, and trade along the Silk Road from Turkey to China would have resulted in much interbreeding between the travelling populations and those living along the Route. Colonization too resulted in much intermingling of genes: the Dutch to Indonesia, the Spanish to South America and the Philippines and the British to just about everywhere else (St Hoyme and Iscan, 1989). Today immigration continues to play a role – in the 50 years leading up to 1988 6.76 million people migrated to the United States (St Hoyme and Iscan, 1989). In 2001-02 there were 88 900 new permanent arrivals in Australia; of the 18.8 million people living here at that time 23.1% were born overseas while an additional 20% were born here but had at least one parent born overseas. During the 2001 census only 27% of the population classified their ancestry as 'Australian' (Department of Immigration and Multicultural and Indigenous Affairs, 2003). Of population mobility there are many other examples that can be cited, including the prehistoric movement of populations that lead to the wide distribution of *Homo sapiens* across the planet. These are just a few examples of how prevalent population movement truly is. As a result of this ever-increasing mobility, samples taken from any given population will tend to be more and more of mixed genetic heritage. A sample taken from the Australian population, being multicultural in nature, will consist of individuals from a vast array of mixed genetic backgrounds. This has the potential to impact significantly on this study and will be expanded upon in the discussion chapter.

A small number of authors have suggested that no specific racial differences in tooth formation actually exist. One such example of this conclusion was reported by Simpson, whose study was based on a sample size of less than 20, and as such lacks credibility as a sound inference (Simpson, 1992). This opinion regarding a lack of racial variability has not been widely endorsed in the literature.

b) Individual Variability in Dental Maturation

Even within a population of similar genetic heritage there will be a range of rates of development due to natural biological variation. Teivens found that within a population there was significant variability – up to four of the stages of the Demirjian system could be observed for a given tooth for a given age across separate cases (Teivens, 1996). Demirjian and Levesque found this variation could be up to five stages for a given age (Demirjian and Levesque, 1980). This corresponds to a chronological age range of up to 6-7 years for a given stage of dental development. Garn found a broad range of variability, up to 3 times as great for the 5th to 95th percentile ranges for a given tooth, than that previously reported (Garn et al., 1959). Mörnstad found variation of up to ± 2.5 years at the 95% confidence interval (Mörnstad, 1995). Haavikko found that the distance between the 10th and 90th percentiles varied between 0.8 and 7.3 years depending on age, sex and tooth type (Haavikko, 1974). Moorrees, Fanning, and Hunt found this variation to be about 2.5 years in 3- to 4 year-olds and up to 5 years in older individuals (Moorrees et al., 1963a). In a later study, working with the same material from earlier studies, Fanning confirmed that individual variation in age for a given stage of tooth development could be up to five years, depending on tooth type and sex (Fanning, 1971). This variation in itself could be attributed to a number of factors, however, as many authors have reported, it is still genetics that plays the largest role in determining the extent of this variation (Garn et al., 1965a; Garn et al., 1965b; Lewis and Stanley, 1960; Merwin and Harris, 1998; Pelsmaekers et al., 1997).

While it may be difficult to separate the relative importance of genetic and environmental factors in developmental variation, it is clear that genetic ancestry and sometimes the temporal physical manifestation of this ancestry, geographical location, have the greatest single influence over the variations in dental development.

6.2.2 NON-GENETIC FACTORS

The growth and development of the human body is affected by a complex interaction of genetic and environmental or non-genetic factors. Studies that have consistently shown that dental development is less affected by environmental factors than is the growth of the skeletal, somatic or sexual systems (Garn et al., 1965b; Lewis and Stanley, 1960; Melsen, 1986; Ryman, 1975). This fact alone allows for a far greater predictability when it comes to age estimation based upon dental development.

The studies referred to above have shown high parent-child or sibling-sibling correlations, which have been interpreted as genetic effects on growth. As previously mentioned, it is extremely difficult to separate out genetic and environmental influences. The intra-familial environment would, for example, be reasonably stable and consistent across any sibling-sibling comparisons. When comparing samples from different familial or racial groups, the environment may differ considerably. With specific relevance to this treatise, immigrants to a country may be seen to share a similar environment but due to social and cultural practices, may eat different types and amounts of food and have differing ideals of family size (Rona, 1981). These factors only complicate any simple concept of environment, as they are often intimately associated with racial groups. In order to keep these effects in context it is again worth noting the common finding that only 10-15% of variation in dental development is due to non-genetic factors. It is these factors that will be explored further here.

When examining the effects non-genetic or environmental influences on growth it serves to classify them into three broad groups; physical, socio-cultural and biological influences. The first includes altitude, temperatures and other climatic factors and will not be expanded upon here as very few, if any studies have addressed the effects that these factors have on tooth development. This does not rule out these influences as potentially significant. Some of the studies reviewed in this treatise compare populations from specific regions to samples from other regions. The inference, which can be made from looking at each of these studies, is that either the intra-sample physical environmental variables are consistent across the sample, or, less likely, that the researchers have simply failed to take these into account. The second group of variables is the socio-cultural group that includes parents' income, education, nutrition, family composition etc. Point's 6.2.2.1 and 2 below fall into this category. The third group is biological in nature and includes birth weight, congenital medical conditions, and the effects of medical treatment, all of which are covered below in points 6.2.2.3 through 5. While it is true that many congenital medical conditions can be considered genetic in their cause, it is their property of being one-off abnormalities and not genetic features of an entire racial group that puts them in this category.

6.2.2.1 Nutrition and Socio-economic Status

Most of our knowledge in the field of the nutritional effects on growth comes from animal studies (Rona, 1981). It has been well documented that, in animal studies, early malnutrition affects both tooth development and tooth eruption (Mellanby, 1928; Schour et al., 1941; Shaw and Griffiths, 1963). Further, tooth eruption has been reported as slightly delayed in malnourished individuals (Fess, 1963), but to a significantly lesser degree than any observed effect on rates of skeletal growth (Billewicz and MacGregor, 1975; Infante and Owen, 1973; Mukherjee, 1973). While Alvarez has supported this finding for deciduous teeth, his study also found that eruption times were advanced in the permanent dentition in his sample of children with mild to moderate malnutrition (Alvarez, 1995). The extreme variability of eruption times, regardless of nutritional status, may well complicate any findings that rely on this measure of dental development.

In a study by Garn et al. examining the effect of caloric excess on dental development the authors found that there was some low correlation (r=0.1 to 0.2) between caloric balance and dental development and that teeth were about one third as responsive to nutritional status as were ossification timing or epiphysial union (Garn et al., 1965b).

In summary, Demirjian stated severe malnutrition affects the skeletal and dental systems but affects the latter to a lesser degree; and, statistically significant correlations between dental emergence and nutrition always remain low (Demirjian, 1986). More studies need to be undertaken based upon rates of dental mineralization and development if the true effects of nutrition are to be understood.

Nutrition and socio-economic status are, in many cases, highly correlated. Malnourished children tend to belong to impoverished societies of low socio-economic status (Banerji, 1988; den Hartog, 1981; Enwonwu, 1973; Mukherjee, 1973), but even in well developed western countries, groups of a lower socio-economic status tend to display higher rates of malnutrition than do groups of higher socio-economic status (Schorr et al., 1972; Stare et al., 1986). As such, most studies that have examined socio-economic status and its relationship to dental development have actually attributed any variations in rates of development to the underlying causes of malnutrition and an increased prevalence of childhood diseases (Enwonwu, 1973; Mukherjee, 1973; Rosen, 1981). In light of this observation, the impact of socio-economic status on dental development will not be reviewed here to any further extent.

6.2.2.2 Smoking

A study on maternal smoking during pregnancy found that while it did significantly reduce mean birth weight, deciduous tooth crown dimensions appeared greatly unaffected reflecting the developmental stability of the teeth

(Heikkinen et al., 1992). Two years later, in a follow-up study, the researchers found that there was an actual reduction in the size of the first permanent molars attributable to maternal smoking (Heikkinen et al., 1994).

6.2.2.3 Secular Trends

With regard to general growth patterns enough information has been published so far to show a secular trend of increasing height and early maturation up to the 1950s in the western world (Cameron, 1984). The best explanation for this is the improvement in social conditions for many populations (Rona, 1981), including better nutrition and freedom from disease in childhood (Goose and Appleton, 1982). This is a theory supported by reports from developing countries where little or no secular trends are evident, reflecting ongoing socio-economic hardship (Proos, 1993). The trend of earlier maturation would seem consistent across all areas of growth, including dental development. A European study by Holtgrave et al. found a slight acceleration in male dental development over the last 30 years (Holtgrave et al., 1997). A US study by Nadler found a comparatively larger mean reduction in dental ages of 1.4 years over the period 1970 to 1990 (Nadler, 1998). One possible explanation for this trend is consistent with the findings of Garn, Lewis and Kerewsky, in that improved nutritional status may accelerate dental development.

6.2.2.4 Fluoride

There have been a number of studies aimed at detecting changes in dental development resulting from variations in community fluoridation levels. Most of these were based upon eruption and not strictly calcification but still warrant closer examination. A number of these studies detected a delaying effect on tooth eruption in those communities who had either taken fluoride supplements or had a fluoridated water supply (Short, 1944; Tank and Storvick, 1964). A study by Scheinen found a fluoride-induced acceleration in eruption times (Scheinin et al., 1964). Still other researchers found no fluoride-related effects on tooth eruption (Carlos and Gittelsohn, 1965; Day, 1940). As eruption times are highly variable, it is unlikely that many of these results are accurate enough to be considered significant. Two published radiographic studies focused on the effects of fluoride on dental development and not just eruption. There were no significant differences in the dental development of the fluoridated versus the non-fluoridated groups in either study (El Badrawy, 1984; Grahnen et al., 1975).

6.2.2.5 Birth Weight

Preterm and low birthweight infants often experience a diverse range of medical complications that affect most of the bodily systems (Usher, 1981). Several of these complications such as pulmonary diseases, hyperbilirubinaemia and hypocalcaemia may have potentially long lasting effects that significantly slow growth during infancy and childhood (Harris et al., 1993; Marlow et al., 1993). This observed reduction in growth rate affects many physical systems including that of the developing dentition.

A number of studies have been undertaken that have shown that some delay in dental development does occur in the permanent dentition. A retrospective study by Harris et al. was undertaken on the dental development of the permanent dentition of American Negroids aged 4 to 7 who were Low Birthweight (LBW <2500g) children. The authors found that only the early forming teeth, the central incisors and first permanent molars, exhibited any significant delay in their development (Harris et al., 1993). A study by Seow on Caucasoid children of Very Low Birthweight (VLBW <1500g) found that, for the age group under 6 years, their mean dental ages were delayed by 0.46 years when compared to that of Normal Birthweight (NBW) children (Seow, 1996). Further, the researcher found that beyond the age of 9 years there was no significant delay in the dental ages of those children of VLBW. This finding is consistent with a more recent study by Backström et al. who, in a study of children with birthweight <2000g, reported no significant delay in the maturation of the permanent dentition when the children were examined between 9 and 11 years-of-age (Backström et al., 2000). One possible explanation for the delay in dental maturity only appearing in younger children is that of catch-up growth. This phenomenon is known to affect somatic and skeletal growth and has been often reported in studies examining retarded rates of somatic and skeletal development and their tendency to diminish with increasing age (Tanner, 1981). In essence, once the initial insult is over or the causative agent is removed, the child resumes growing, but at a rate well above that to be expected for their age. This rate tends to then revert to normal once the level of development of the child has reached what would otherwise normally have been obtained at a given age. This was a significant conclusion in the Seow study that is consistent with the results of others. Looking at the reverse situation, a study by Bailit and Sung found that children of higher birthweight born to older mothers had a slightly advanced dental development; although significant, the correlation between the factors was very weak (Bailit and Sung, 1968).

Data on the effects of birthweight on the deciduous dentition is more scarce. A study by Seow et al. found that the development of the deciduous dentition of LBW and VLBW children was clinically delayed. However, when the ages of the children were adjusted for the premature birth, giving a true biological age, no significant differences in the numbers of erupted teeth between the preterm and reference sample were observed (Seow et al., 1988). Most studies of this type, including that of Seow, rely upon eruption times to measure dental development. Although not as accurate as other methods, observation of eruption timings avoids exposing the child to unnecessary x-rays.

6.2.2.6 Congenital Conditions

There are over 600 multisystem genetic syndromes that have a major orofacial component. The varied expression of these may include hypo- and hyperdontia, delayed or accelerated development and eruption and structural defects of the oral tissues (Lukacs, 1989). Additionally, a multitude of endocrine and metabolic disorders also have a significant effect on dental development. It is in this area that the main body of research in this field has been undertaken. A study by Keller et al. investigated many such disorders (Keller et al., 1970). In this study, the researchers found that a number of disorders, anecdotally associated with changes in rates of dental development, had no consistently significant impact on dental development. Specifically, patients with diabetes mellitus, lymphocytic thyroiditis, or hypo- or hyperthyroidism did not display changes in the rate of dental development significantly different from the control group. The findings regarding hyperthyroidism were consistent with those of Sklar (Sklar, 1966). The findings regarding hypothyroidism were consistent with those of Edler (Edler, 1977), but contrary to those reported by Garn et al. who found dental developmental delay by as much as 8 years in such cases (Garn et al., 1965a). This difference in findings may be attributed to Garn's group of hypothyroid patients being expanded to include many more subjects who fitted the classification of ‘cretins.’

Keller found that hypopituitarism (resulting in growth hormone deficiencies), did have a significant impact on dental as well as skeletal development. These findings were consistent with many studies including the separate studies undertaken by Garn et al., Krekmanova et al., Aren et al. and Vallejo-Bolaños et al. (Aren et al., 2003; Garn et al., 1965a; Krekmanova et al., 1997; Vallejo-Bolaños et al., 1999). The other main disorder where Keller found significant delay in both dental and skeletal development, when compared to the control group, was that of 'constitutionally delayed puberty.' This was consistent with the findings in a study by Gaethofs et al. (Gaethofs et al., 1999). In such cases, the rate of growth of all systems, including the dentition, is retarded compared with population norms (Tanner, 1962).

Finally, Keller found a number of disorders where, although both dental and skeletal rates of growth were affected, the effect on the skeletal growth was significantly greater than the small effect on the dental growth. In some cases there was no dental but a profound skeletal effect. These disorders included; juvenile myxoedema, where skeletal delay was considerably more than the dental delay; adrenogenital syndrome, where no effect was found on dental development but a considerable delay in skeletal development occurred; and constitutionally precocious puberty, where although skeletal growth was significantly advanced, dental development was within normal ranges - which is consistent with the findings of Garn et al. (Garn et al., 1965a).

The findings of Keller and others support the idea that the dental system is not affected to nearly the same extent by factors that greatly accelerate somatic, sexual or skeletal maturity. Despite conflicting results regarding hypothyroidism, Garn et al. are also of the opinion that in delayed growth dental delay is far less marked than any retardation in skeletal status. This is an opinion shared by many, including Demirjian who stated that, even serious endocrinopathies, which severely retard somatic growth and maturation, exert only a minor effect on the dentition (Demirjian, 1986).

As stated at the beginning of this section, there are literally hundreds of systemic conditions that have dental manifestations. Studies in this area are too numerous to review but have included findings that many conditions significantly slow the rate of dental development. These include; renal failure (Jaffe et al., 1990); cleft lips and palates (Harris and Hullings, 1990; Heidbüchek et al., 2002); cerebral palsy, both the spastic and athetoid types (Ozerovic, 1980); Glucose-6-phosphatase deficiency, also known as hepatorenal glycogen storage disease (Loevy, 1983b); acrocephalopolysyndactyly type II, also known as Carpenters Syndrome (Blankenstein et al., 2001); and cleidocranial dysplasia, where a mean delay in dental development of 3 years was reported (Seow, 1995a). Other studies found that many other conditions resulted in an accelerated rate of dental development, such as Turners Syndrome (Midtbo and Halse, 1992), cerebral gigantism (Crosher, 1986), and amelogenesis imperfecta (AI) (Aren et al., 2003; Seow, 1995b). Seow suggested that the acceleration in dental development of cases with AI may be a reflection of the decreased time required for lesser amounts of enamel mineralization. Finally, a number of studies found that some conditions, that were previously thought to affect dental maturation, actually have no significant impact on the rate of dental development at all, such as; rickets (Schour and Seow, 1995; Tracy and Campbell, 1968) and cystic fibrosis (Primosch, 1980). This last finding was inconsistent with that of a similar study by Mahaney, who found that while there was an observed delay in children with cystic fibrosis, it was not consistent with the pathological aetiology of the disease and probably due to an endocrine-mediated pleiotropic effect of the cystic fibrosis locus (Mahaney, 1986). This last study serves to demonstrate the complicated nature of the cause and effect relationship between medical conditions and dental maturation.

Many prenatal events have a significant impact on dental maturation. These include: infections such as rubella and influenza; physical injuries, including those from radiation and of thermal and hyperbaric origins; respiratory distress caused by hypoxia, carbon monoxide poisoning and carbon dioxide excess; the actions of many drugs and chemicals, for example, Thalidomide and Thiadiazole; maternal pathologies such as uterine tumors and uterine inflammation, even emotional disturbances and stress (Harring and Lewis, 1961). While most of these factors cause morphological changes, a significant number will also delay tooth development (Lundstrom et al., 1962). For example, studies by both Evans and Lundstrom et al. reported significant delays in dental development of children who were exposed to maternal rubella in the first trimester (Evans, 1944; Lundstrom et al., 1962).

6.2.2.7 Medical Treatment

Most research into the effects of medical treatment on the rate of dental development has centred on chemotherapy and radiotherapy. There are however, a number of exceptions. A study by Lehtinen et al. into juvenile rheumatoid arthritis found dental maturity in these cases to be advanced over chronological age (Lehtinen et al., 2000), and that this could be partly attributed to long-term treatment with cortisone, as the effect had been reproduced in animal studies (Kiely and Domm, 1997). A separate study by Myllärniemi into the effects of growth hormone treatment for hypopituitary patients found that the lag in dental maturation observed in the patients pre-treatment slowly diminished once treatment commenced (Myllärniemi et al., 1978). These findings were consistent with those of other studies (Bevis et al., 1977).

The treatment of choice for many malignant childhood diseases is a combination of radio- and chemotherapy. A number of studies have shown that both these treatment modalities have a significant impact on dental development, producing partial anodontia, microdontia and root stunting (Dahllöf et al., 1994; Goho, 1993; Kaste et al., 1998; Näsman et al., 1997). In fact, Kaste et al. found that 71% of patients displayed significant dental abnormalities post-treatment. Most patients receive a combination of both radiotherapy and chemotherapy so it is often difficult to distinguish between the effects on dental development of each treatment, however, one group of researchers, Näsman et al. did find that the irradiation caused more severe effects than chemotherapeutic agents (Näsman et al., 1997). Kaste et al. found that while radiation effects on the teeth are limited to the area of irradiation, chemotherapy has a generalized impact on the entire dentition (Kaste et al., 1994). Further, Näsman et al. also found that the most extensive and severe disturbances occur when irradiation is delivered during the early stages of tooth development, that is, when the children are aged less than 6 years.

While these studies all found significant impacts of treatment on dental development, the studies were more focused on morphological characteristics than rates of maturity. The study by Näsman et al. was one of the few to examine 'dental age,' albeit measured by tooth eruption. The researchers found that despite the morphological changes to the teeth, including the complete arrest of root development in some cases, eruption times were not significantly affected. In light of the reported root length shortening and root development arrest, the use of age estimation techniques based on stages of tooth development may not be applicable in such cases.

Finally, another important consideration is that it is well documented that growth failure and growth hormone deficiencies are often reported complications of acute lymphoblastic leukaemia treated with radiotherapy (Kirk et al., 1987), as well as in long term survivors of childhood bone marrow transplants (Sanders et al., 1986). As seen earlier, these conditions alone have an impact on rates of dental maturation. These studies have served to illustrate the complicated nature of the impact of malignant disease and its treatment on dental maturation.

6.2.3 SEX

Within any given population there is also a clear difference in the rate of development based on both age and sex. When considering somatic growth it is an accepted fact that girls are generally more advanced than boys, up to the pre-adolescent years (Demirjian and Levesque, 1980). Studies of the pattern of dental calcification have revealed a similar trend (Anderson et al., 1976; Fanning, 1961; Moorrees et al., 1963a; Rosen, 1981; Chaillet et al., 2004). These researchers studied the timing and rate of development of the deciduous dentition and all arrived at similar conclusions. That is to say, that there is almost no difference in the timing of the calcification between the male and female dentition in the early stages, but it is the completion of root formation where an obvious sexual dimorphism exists. It is here that these two studies diverge in opinion. The former found the females advanced over the males by 2 months, the latter found the reverse to be so. A study by Gleiser and Hunt (Gleiser and Hunt, 1955) that looked at the development of the permanent molars found females completed root formation, on average, 4 months earlier than males. A similar study was undertaken by Garn et al. (Garn et al., 1958), who found that although males preceded females in the completion of first molar root completion, it was females that preceded males in the completion of the other teeth. Nolla, although using a slightly different classification system, found females to be advanced over males at all stages of permanent tooth development (Nolla, 1960). A study by Thompson et al. corroborated the findings that a significant sexual dimorphism exists, particularly in the later years of development, with females being advanced over males (Thompson et al., 1975), as did a study on German children by Frucht (Frucht et al., 2000), and a study on American children by Rosen (Rosen, 1981). A recent Belgian study found that females were advanced over males but that the greatest differences in dental maturity occurred at 12 years, after which time, males started to mature faster than at earlier ages, and thus reduce the maturity differences (Chaillet et al., 2004). In analysing the results of the above studies, it can be seen that the authors generally agreed that the early stages of tooth development are almost the same for both male and female, while the sexual dimorphism in developmental rates occurs at about the crown completion stage and continues to increase during the root development stage. Demirjian and Levesque attributed any differences in the results of the studies to small sample size. In considering the results from many independent studies, Demirjian and Levesque found the mean age for apex closure of the first molar distal root is at 9.5 years and 8.8 years for females and males respectively, representing a significant sexual dimorphism (Demirjian and Levesque, 1980).

The Demirjian and Levesque study further set out to examine the sexual differences in dental development for each permanent tooth in a large, racially homogeneous sample. They found similarity between the sexes in the early stages of development (Demirjian Stages A, B, and C). At the crown completion stage (Stage D) females were advanced over males by an average of .35 years. For the following stages through to apex closure (Stage E, F, and G) females were advanced over males by an average of .54 years over all the teeth, the difference being greatest in the canines at .90 years. These results are consistent with the conclusions of Garn (Garn et al., 1958), Fanning (Fanning, 1961), Moorrees (Moorrees et al., 1963a), Sapoka (Sapoka and Demirjian, 1971), Thompson (Thompson et al., 1975), and Rosen (Rosen, 1981), in as much that the greatest degree of sexual dimorphism occurs during the root formation stages, there being negligible difference during crown formation.

6.2.4 AGE

As would be expected, the variation in dental development increases with the increase in median age. The study by Garn et al. (Garn et al., 1959) referred to previously also examined this phenomenon. They found that the early developmental stages of early forming teeth were notably less variable than the later developmental stages of the later forming teeth. These observations are corroborated by the results of Demirjian and Levesque discussed previously (Demirjian and Levesque, 1980).

6.2.5 A CONSTANT RATE OF DEVELOPMENT ?

A number of authors have proffered the theory that it is tooth size, and not rates of tooth formation, that are responsible for variation in levels of dental maturity. Gleisser & Hunt suggested that, despite females being dentally advanced over males of the same age, within a given population the rate of tooth development was relatively constant (Gleiser and Hunt, 1955). The authors explained that female teeth were finished forming at a slightly younger age than those of males, but female teeth were also slightly smaller than males, so the actual 'velocity' or rate of development was the same. Seow suggested that this same phenomenon may be the cause underlying the 'advanced dental maturity' of patients with Amelogenisis Imperfecta – if there is less enamel to be made, the tooth will be finished forming sooner (Seow, 1995b). Skeletal growth studies have reported similar findings. Roberts found that the rates of growth of siblings was similar even though at various stages some appeared to be advanced in maturity over others (Roberts, 1981). In these cases it was just the timing of the commencement of this growth, the switching on of the growth gene, that resulted in variations in measured levels of maturity.

If the sexual dimorphism in tooth dimensions is greatest for the roots, the theory offered by Gleisser and Hunt would be consistent with the observation that the greater sexual dimorphism in dental age is observed in the later years of growth, being the period when the roots of many of the teeth are being formed. Conversely, as the amount of sexual dimorphism in crown dimensions is small, so are the differences between males' and females' dental maturity during the early years when the crowns are being formed. While there are some studies that have explored the sexual dimorphism of tooth crown dimensions, little conclusive data could be found on tooth root comparisons. As such further studies are required if the Gliesser and Hunt theory is to be widely accepted.

It is possible that if the rate of dental development is relatively constant for males and females, perhaps it does not vary too significantly between 'races'. If this is the case, then the observed variations in dental maturity between samples from different regions may be more due to variations in tooth size than to variations in formation rates. It is possible, however, that similarity in rates of dental development is limited to individuals of common recent ancestry and that the world wide observed differences in dental maturity are a result of a combination of many factors.

6.3 METHODS OF AGE ESTIMATION BASED ON TOOTH DEVELOPMENT

The previous section has highlighted a common theme – many factors that may have a significant effect on somatic, sexual and skeletal development have little effect on the commencement, rate or sequence of dental development. Over the years many authors have realised the utility of systems of age estimation based upon the actual development of the teeth. As early as 1935 Schour and Hoffman found that the pattern of calcification of the dentition under normal conditions acts as a reliable indicator of the pattern of growth (Schour and Hoffman, 1935), shortly after which the pattern of dental development was used to estimate age (Schour and Massler, 1941).

In its development each tooth follows the same sequence. It is this sequence that can be arbitrarily broken down into consecutive stages. In an attempt to define the requirements of any such stages Demirjian stated that these stages should:

a. describe the major developmental stages of the tooth,
b. be clearly defined (not just on the basis of length increases), and
c. be objective enough to be reproducible (Demirjian, 1986).

It is the relative consistency of the process of tooth development that is a major contributing factor in the widespread use of these development based age estimation systems. It is well established that the progressive cusp-to-apex calcification pattern of teeth surpasses all other anthropological and forensic methods of estimating chronological age in children under the age of

14 years (Sopher, 1976). What follows is a review of the significant studies undertaken in this area. Some researchers sought to develop age estimation methods while others simply sought to chronicle the development of the dentition and provide 'average age of attainment' standards by which one could gauge the dental growth of a child. The use of this latter group of techniques to estimate age, although not the authors' original intent, has been widespread. As such, these studies too have been reviewed in this section.

6.3.1 Logan & Kronfeld

The study by Logan & Kronfeld in 1933 was commenced in response to a practical problem (Logan and Kronfeld, 1933). It had been noted that it was not uncommon for growth deformities and underdevelopment of the teeth and jaws to occur in the years following the surgical correction of congenital clefts of the maxilla and upper lip. It was suggested by the authors that a thorough understanding of the position, timing and sequence of tooth development was necessary if the transmaxillary wires were to be surgically positioned without damage to unerupted teeth. A cross sectional study using histological sectioning and radiographic examination of 0 to 6 month olds was devised. During the course of the study this age range was first extended to 2 years, being the endpoint of the window for the surgical procedure of choice. Once the utility of this information to specialists and general dental practitioners alike was realised the age range was then extended up to 15 years, being the end point of the development of the first seven permanent teeth.

The authors drew attention to the gross inaccuracies of previous studies, as the results were based upon examination of dried skulls, radiographic examination or dissection only. Broomell & Fischels dissected out fresh specimens, which was very good for providing information on the degree of dental development but lacked the accurate detail required for the exact positioning of the tooth buds within the jaws (Broomell and Fischelis, 1917). Legros and Magitot (Legros and Magitot, 1893), upon whose tables most dental practitioners of the time had relied upon for about 40 years, were also flawed. They had used dried skulls and as such, they had not gathered accurate information on the timing and sequence of dental development. Their resulting tables contained errors of the commencement of tooth formation of up to 2 years. Contemporary studies by Churchill (Churchill, 1932), Pierce (Pierce, 1887) and Black (Black, 1908) also resulted in flawed information being hailed as accurate. This information was summarised in tabular form and was reproduced earlier in Table 6.1.

With the above information being the best of the day, Logan and Kronfeld undertook their study to accurately record the age of commencement and the relative order of the calcification of all teeth, not the specific degree of dental development for any given age. Their reason for this approach was that if factors such as nutrition, birth weight and general health did affect dental development the relative development between the teeth would be the same. This approach was particularly applicable to their sample as most of the subjects were chronically ill prior to their deaths.

The Logan & Kronfeld study was based on the examination of 25 fresh post-mortem specimens. However 19 of these were under 2 years-of-age. Radiographs were taken and serial histological sections made. The authors published a detailed account of the positioning and relative development of the human dentition. They found no consistent ratio between the degree of calcification and the age of the child although they suspected this may have been due to the childrens' chronic illnesses.

The observations of Logan & Kronfeld regarding the staggered commencement and continued development of teeth, was confirmed by their observations of the relative positions of hyperplastic defects in certain teeth depending upon the age of the child at the time the defect occurred. The accuracy of the ages given for the various stages of tooth development was up to ± 1.5 years with no sex differentiation. This study provided the dentists of the day with the information required to judge the level of development of a child and to measure it against expected norms.

6.3.2 Schour & Massler

In 1941, Schour and Massler published an important study that summarised the development of the human dentition (Schour and Massler, 1941). It was the inclusion of a chart showing the development of the human dentition from birth to 35 years that made this study notable – the chart is still widely used today. It was the authors' intent to detail the development of the dentition, being information that the general dentist would 'find useful in everyday dental practice.' The summary of this information into a pictorial or 'atlas type' chart provided the profession with a useful tool that would not only be used in every day practice, but would also prove useful in estimating the age of an individual. The method involves comparison of a radiograph of, preferably, the entire maxilla and mandible to diagrams depicting the stage of the development of the dentition that can be expected at each year in the life of a child. By matching the radiographic image to a specific diagram the estimated age of the child is that listed with the associated diagram. This chart is reproduced in Figure 6.2 below.

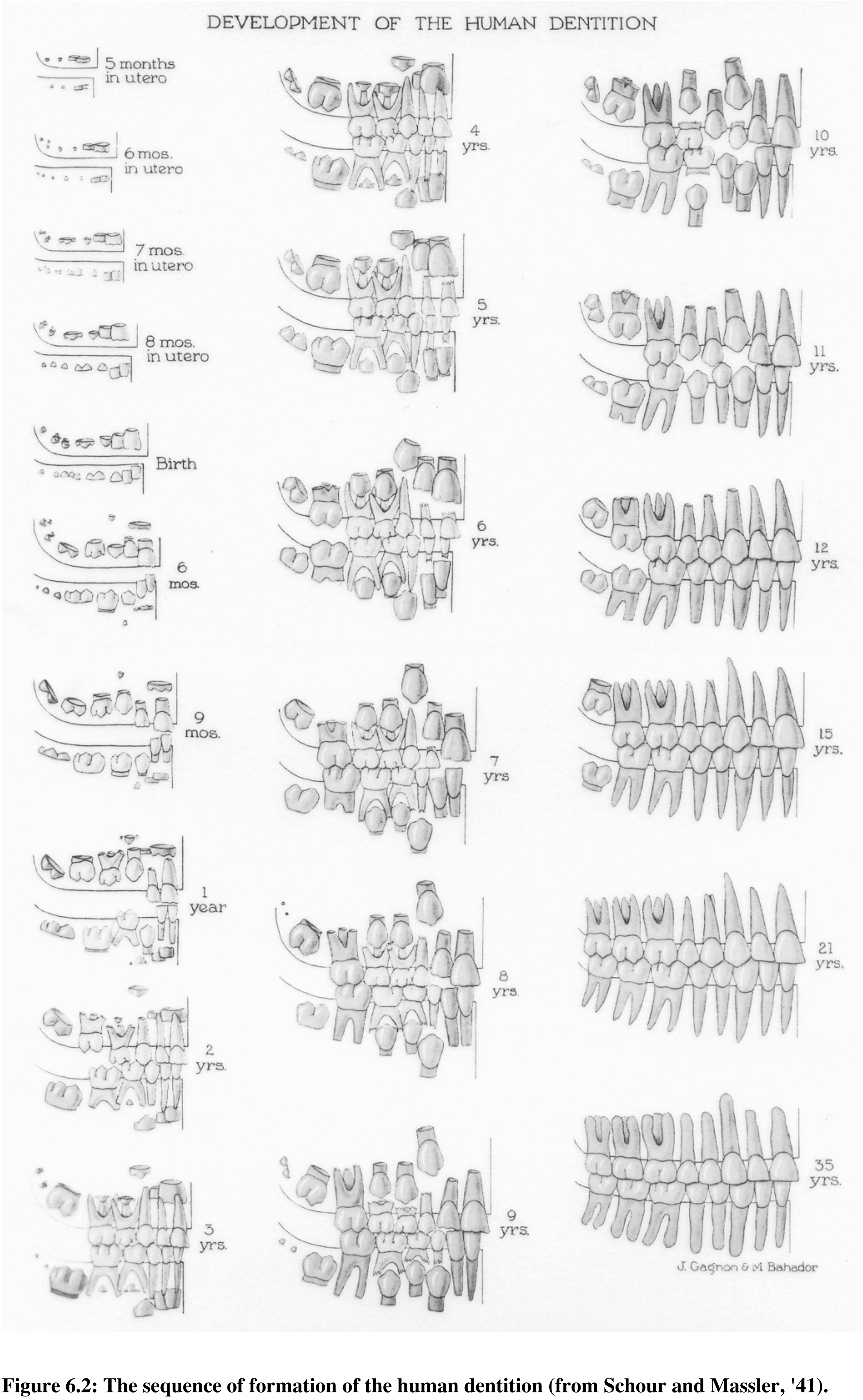


Figure 6.2: The sequence of formation of the human dentition (from Schour and Massler, '41).

The advantages of using this system to estimate the age of an individual are; that it is non-destructive, being able to conduct the assessment on radiographs of the jaws; it is simple and does not require any specialised training to recognise specific stages of development, as required in many of the more recently developed systems; and it does not require the use of specialised equipment beyond an x-ray apparatus.

Valid criticisms of this method include the fact that it is based on the work of Logan and Kronfeld (Logan and Kronfeld, 1933) and as such suffers from the same very small sample size, being one sample per age group up to 15 years. In addition, the cases were of chronically ill, institutionalised children and no differentiation is made between male and female. In assigning a different diagram to each year of growth, the range about a mean age can only be ±6 months, and as will be seen this may well be too narrow a range to be credible. Finally, being an 'atlas type' system any comparison is subject to a higher degree of inter-observer disagreement when compared to systems that rely on objective physical measurements. However, the wide applicability, despite the sample on which it is based, may be testament to the relative stability of the pattern and rate of dental development regardless of the impact of 'environment' or disease on growth.

Despite the shortcomings, the charts still seem to provide a clinically acceptable estimate of age and are still widely used today (Ciapparelli, 1992). For this reason this method was included in the present study.

6.3.3 Gleiser & Hunt

This study, undertaken in 1955 was a radiographic, longitudinal study that examined the development of the first permanent molar of 25 male and 25 female children (Gleiser and Hunt, 1955). They authors divided the stages of development of this tooth into 16 stages. It is worth noting that the authors mention the use of 13 to 16 stages, depending upon which part of the article one refers. They were, however, one of the first groups of researchers to divide the process of development of each tooth onto a number of defined stages. Instead of estimating at what age a particular stage of development had commenced, the authors recorded the age of every child in whom a particular stage was observed. They then calculated the standard deviation of the age for each of the stages of the development of the tooth. The authors noted a period of rapid growth in the development of the teeth during the period of 1/3 – 1/2 root length formation. More importantly, they also noted an increasing sexual dimorphism in dental development with increasing age but that the rate of growth was probably very similar. They noted that in a study by Selmer-Olsen of 123 males and 122 females the mean mesio-distal diameter of the female teeth was 96% that of the male teeth and that the mean root length of the female teeth was 94% that of the male teeth (Selmer-Olsen, 1949). They made the further observation, based on the work of Hurme, that for roughly equivalent stages of dental development the average girl is 95% as old as the average boy is (Hurme, 1948). From their own study they observed that teeth underwent a period of rapid growth during their development and that for females this period was 96% as long as that of the males. Their conclusion was that the absolute incremental rates of tooth development are approximately the same for male and female, because while the females had a shorter period of rapid growth they had a smaller absolute size of the tooth to achieve, thereby completing the development in a shorter time frame.

Noting that the rate of occluso-apical growth was not constant over each stage, they graphed occluso-apical height (taken from a study by Black (Black, 1902)) against age to estimate the growth rate at each stage. They then plotted clinical emergence (taken from another study) against age. As with the earlier study by Brauer & Bahador (Brauer and Bahador, 1942), Gleiser and Hunt also concluded that emergence was not as good a predictor of chronological age as calcification of the teeth was. As such, if the stage of development of the first permanent mandibular molar is ascertained according to the predefined criteria of the authors, one can refer to their chart of 'stage of dental development against chronological age', and gain an estimate of the chronological age of the child. The use of this method is fast and simple because it relies on the analysis of just one tooth but this is also its main disadvantage. If any growth abnormality has occurred with either (or both) of the mandibular first permanent molars the system cannot be used accurately, if at all. Interestingly, the comparison between skeletal age, dental age and chronological age from this study showed that where delays in skeletal maturity occurred the effects were far less prolonged in the dental development of the same child.

6.3.4 Nolla

Nolla felt that it is important for the dentist to have a good understanding of the development of the dentition and, as such, undertook this study in order to provide information that would aid the dentist in assessing the progress of the dental development of young patients (Nolla, 1960). In order to do this the author sought to develop norms that displayed the average development of teeth for a given age for males and females, and to develop tables that could be used to estimate chronological age based on the degree of observed dental development. The method used involved the analysis of a set of annual, serial radiographs of 25 female and 25 male children giving the total number of radiographs of 1746 for the female sample, and 1656 for the male sample. Nolla divided the stages of dental development into ten stages through each of which every tooth passed, these are depicted in Figure 6.3 below. Each stage was also given a numerical score.

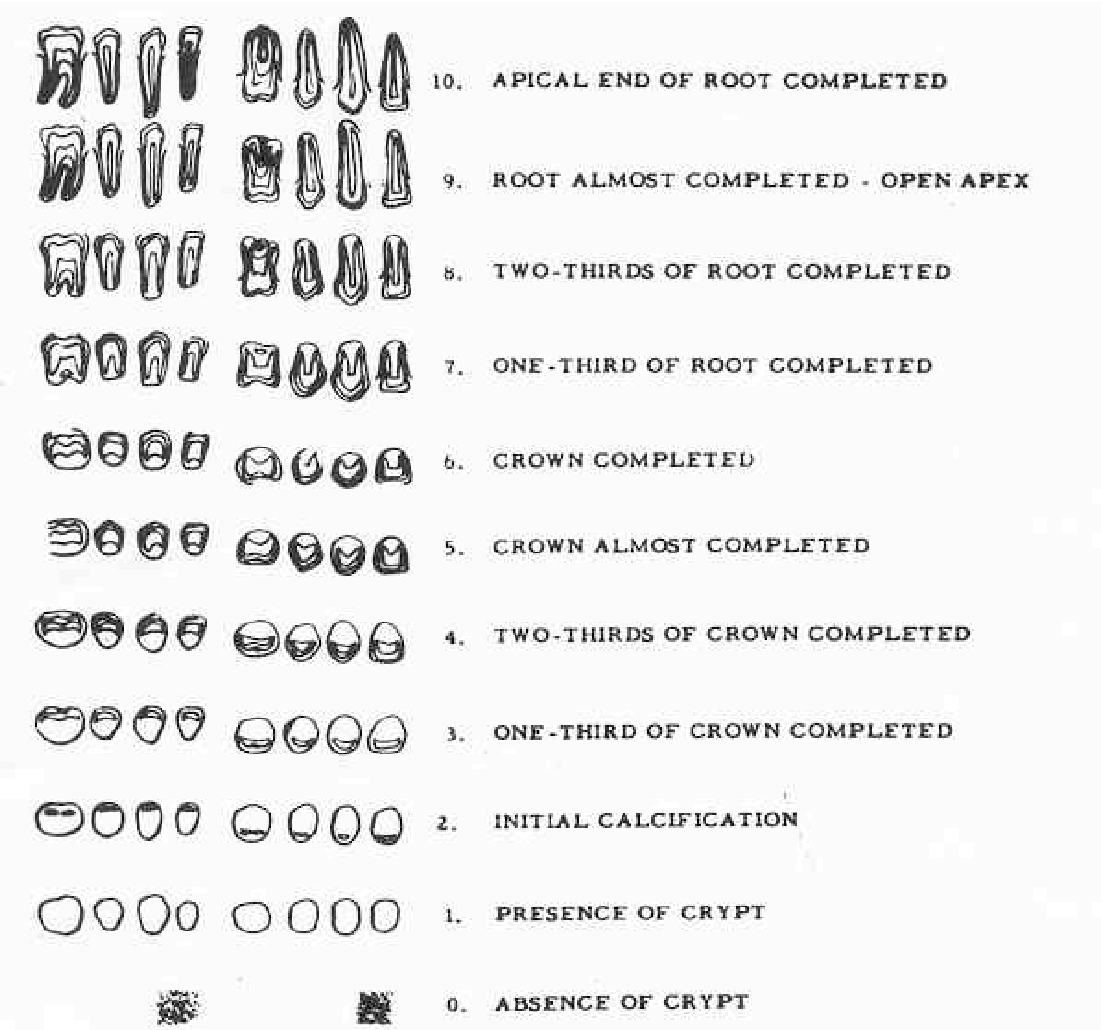


Figure 6.3: Stages of development of the mandibular and maxillary teeth (from Nolla, '60).

The permanent maxillary and mandibular teeth as seen on the radiographs were then analysed and each tooth was assigned the appropriate stage and score. Only the teeth from one side of the mouth were used and the third molars were excluded. The scores were totalled to give a combined 'sum of stages' score. The individual tooth scores were used to develop norms for the maturation of the individual permanent teeth, whereas the summed scores were used to develop norms for the scored level of dental development for a given age. In this way a dentist could determine the stages of development of the teeth of a child from a radiograph, convert the stages to the appropriate scores and use the sum of the scores to estimate the age of the individual by direct reference to the Nolla conversion tables. The same process can also be used for individual teeth scores.

The advantages of this system are that there are ten graphically described stages that can be visually matched to the appearance of the developing teeth on a radiograph. As such, x-ray equipment aside, no additional specialised equipment is required and the system is simple to use. These few advantages are unfortunately outweighed by the disadvantages which include; the requirement for absolute and estimated measurements of the root formation - in order to measure '1/3 root formed' you need to estimate how long the fully formed root will be; the racial mixture of the sample on which the study is based was not reported and as such limits its applicability; and finally, because of the format of 'expected norms' no prediction error values can be obtained for any estimates made. A recent study by Bolaños et al. proved quite successful despite these shortcomings (Bolaños et al., 2000). Using the Nolla standards, but with only three teeth, the researchers reported prediction errors of only ±1.3 to 1.4 years in cases aged under 10 years. Over this age range the error increased to just ±2 years at the 95% confidence interval. The researchers also found, using kappa, that the inter- and intra-observer agreement was 'substantial' to 'excellent.' Being in agreement with other studies (Staaf et al., 1991), these results appear promising and warrant further investigation and validation on racially differing populations.

6.3.5 Fanning

Fanning stated that chronological age can be misleading with respect to dental maturity, in that they may not coincide if the growth of the child is advanced or retarded for their age (Fanning, 1961). Fanning undertook this qualitative study to provide norms for the ages of attainment of specific stages of tooth development and root resorption. It was the intention that these norms, including percentile bands, be used in conjunction with the known chronological age in clinical diagnosis and treatment planning by dentists and orthodontists.

The study was longitudinal in design, taking and analysing lateral skull radiographs every 3 months for the first year of life then every 6 months until the child reached 11.5 years. To provide useable images of the anterior teeth intraoral radiographs were taken of the maxillary and mandibular incisors every 6 months from 4 to 11.5 years. The subjects studied consisted of 48 males and 51 females.

Fanning designated a number of stages of development for each tooth based upon the fifteen stages described by Gleiser and Hunt. Fanning described up to twenty stages depending on tooth type: the development of the permanent incisors was covered in twelve stages, the permanent molars required all twenty to be used, while the deciduous teeth development was described by only seven stages.

Fanning derived the mean age for her sample at which each stage of development was reached by each tooth. She also calculated the 10th, 25th, 75th and 90th percentile bands. This process was repeated for root resorption of the deciduous teeth. As a sexual dimorphism was noted, tables were divided into results for male and female. By way of example, only the table for males has been included in Figure 6.4 below.

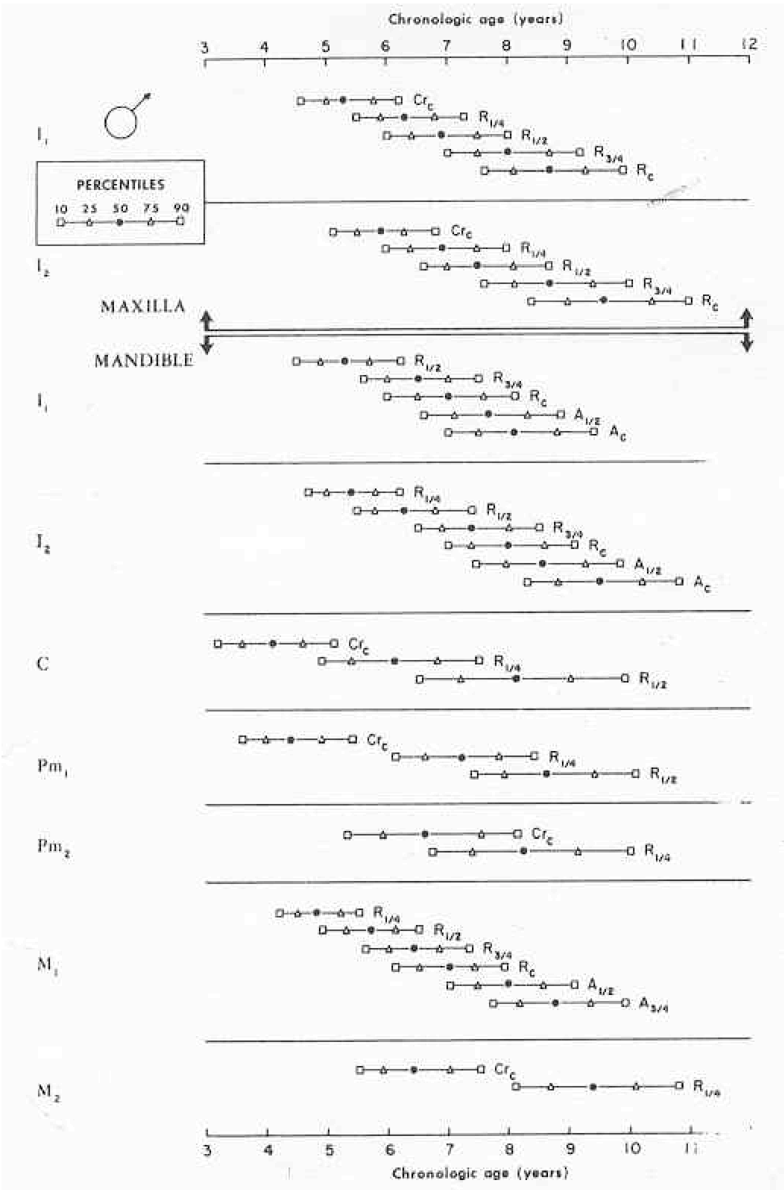


Figure 6.4: The chronology of tooth formation during pre-adolescence in 48 Bostonian males. Cr_c=crown formation complete, $R_{1/4}$=root 1/4 formed, $R_{1/2}$=root 1/2 formed $R_{3\text{-}4}$=root 3/4 formed R_c=root completely formed (from Fanning, '61).

The deviation from the mean for the 10th and 90th percentiles ranged from approximately ± 9 months for one of the stages of root formation of the first permanent molar up to ± 18 months for one of the stages of root formation of the canine.

This study was one of the first to study the pattern, timing and rate of dental development of a large sample. Consequently, the tables derived have been used to estimate chronological age for the stage of dental maturity described even though this was not the original intention of the author. This study proved useful for this purpose because it relies on development times and not emergence times. This study is, however, limited in its application in that it only spans the ages 0 to 11.5 years, an error of up to 3 years is possible and there is no way to consolidate the results for each individual tooth to provide an overall estimate of chronological age. Further, the allocation of one of up to twenty stages is very time consuming, and is often difficult to consistently apply. While Fanning described a 73% agreement she did not take into account chance expected frequency of concurrence. Again it is important to note that the author did not intend that the results be used to estimate chronological age, rather she sought an aid in treatment planning and diagnosis.

6.3.6 Moorrees, Fanning and Hunt

In this study the authors noted the usefulness of using dental maturity to estimate the age of skeletal remains (Moorrees et al., 1963a). Similar in design and building on the work of Fanning, this longitudinal study sought to expand the age range covered up to 17-18 years and to simplify the rating system by only using fourteen stages. These stages were arbitrarily selected but are consecutive. The aim was again to obtain norms for the attainment of the 14 stages of development for each of the 8 mandibular and maxillary incisor teeth. 48 males and 51 females were used for the age range up to about 10 years, then a separate sample of 136 males and 110 females was used to follow through the development of the dentition to final stages at about 18 years. All subjects were Caucasoid North American children.

The authors derived a mean age of attainment for each stage of each tooth and graphically represented the results including ± 2 standard deviation age limits.

The advantages of using this system over earlier systems appears that the smaller number of stages and reported high intra-observer reliability make for a more consistent and easily applied rating system. Other researchers have applied this method with quite accurate results, predicting ages within ± 0.2 years (Smith, 1991). Saunders rated this system harder to use than that of Anderson (Anderson et al., 1976), but found that it provided a more accurate age prediction than either the Anderson method or a range of skeletal ageing techniques (Saunders et al., 1993). In this study by Moorrees Fanning and Hunt the quoted intra-observer agreement figure of 75% for incisors and 90% for posteriors made no allowance for chance expected concurrence. Consequently, the actual level of intra-observer agreement would be less.

The provision of standards for both the deciduous and permanent dentitions by the authors allows the system to be used over the widest possible range of cases from birth to maturity. These features have lead to the recommended use of this system in both archaeological and forensic settings (Saunders et al., 1993).

One of the main disadvantages of using this technique is that it relies on absolute measurements such as root 1/4, 1/2 or 3/4 formed. To accurately measure this, one needs to know the final length of the particular root in question. To elaborate, in order to estimate the stage of, say, root 3/4 formed, one would need to compare this to either later images of the same tooth, or to an image of an adjacent, more advanced tooth to get an idea of how long the fully developed root will be. This will then enable the clinicial to estimate the length of the root in question at 3/4 of this. Both of these choices have their own short comings; the former may be impossible if the case at hand is a forensic one, making the availability of future images later on in the development of the case's dentition an impossibility; and, the latter only provides a rather crude estimate of the final root length as not all adjacent teeth have the same final root length.

Another disadvantage of using this system is, as the authors pointed out, that because of the question of the applicability of these results to a given population and the variation between the maturity of each tooth as compared to the norms, it may not be possible to estimate a specific dental age. What can be estimated is a standard maturity score which can be used for comparison between cases and not for estimating an absolute age. The range of age variation from the norm for 2 standard deviations (SD) was about 3-5 years for teeth in the root formation stages and up to 8 years in the apical closure of third molars. These age range variations may well be too large for this system to be useful in determining a comparative score, let alone a dental age. Finally, 'mean age of attainment' is not what is actually being assessed. The measure of mean age of attainment is actually the mean of all the ages for a given tooth that are classified as having reached one specific stage without having passed on to the next stage. While not truly a disadvantage of the system, the misnomer may lead to the misinterpretation of results when this system is used.

6.3.7 Wolanski

Interested in the effect of environmental factors on developmental traits, Wolanski sought to develop a more accurate method for evaluation of physical development (Wolanski, 1966). He chose to base his technique on dental development and more specifically to build on the work already done by Moorrees, Fanning and Hunt.

The author used the same fourteen stages defined by Moorrees, Fanning and Hunt, as well as their sample. In addition to the previous studies, the author assigned a numerical score to each stage of development. Each of the radiographs as described in the previous sections was analysed, stages and scores assigned for each of the eight mandibular teeth and two maxillary incisors for each case, and finally all tooth scores for each case were summed to give a final individuals score. The results were plotted graphically as the norm ±2 SD. By way of example, only the female chart has been reproduced below.

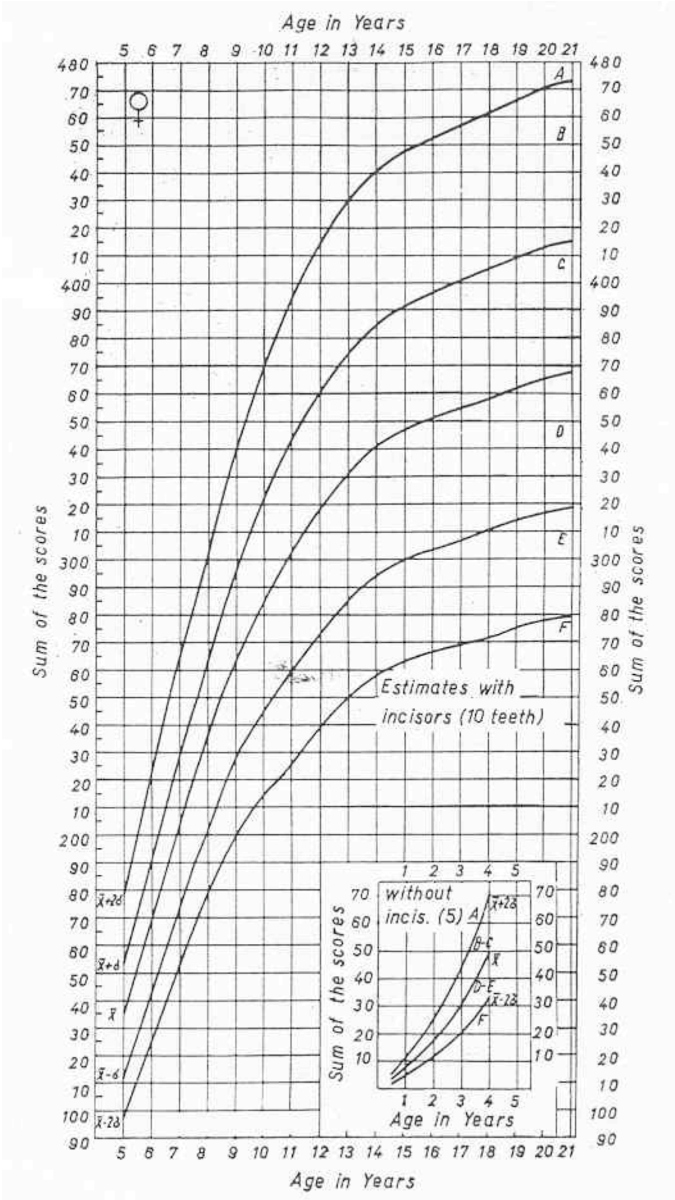


Figure 6.5: Chart for estimating dental age in females. Figures on the ordinate of the graph proper represent the scores for all 10 permanent teeth used in the Wolanski study, and in the insert for just 5 permanent teeth (from Wolanski, '66).

The intention of Wolanski was, that by using his method to arrive at a maturity score, the chronological age of an individual could be estimated by reference to the above curves. The advantages of this technique are that it can easily be used to estimate chronological age from a derived maturity score, provided the assessor is familiar with the defined stages of development and that some training is undertaken to establish a degree of inter/intra-observer consistency. Importantly, this method also overcomes the problem associated with using the atlas type diagrams of Schour and Massler in that it takes into account the possibility that there may be varying rates of development for different stages for different teeth. Where it is often hard to find an exact match for all teeth in any given Schour and Massler diagram, this method, by attributing a numerical value to the degree of development, overcomes this problem.

This method obviously shares some of the disadvantages of the system of Moorrees, Fanning and Hunt, on which it is based. While the number of stages remains at fourteen, they still require an absolute measurement to estimate the stage of root development. The main disadvantage to using this system is the potential error involved in the final age estimate. At the younger end of the spectrum the range of ±2SD is about 4 years, which is not dissimilar to many of the other techniques in use today (Mörnstad et al., 1994b), however at the more mature end of the scale the range of ±2SD is greater than 12 years. This degree of error renders the application of this technique questionable.

6.3.8 Calonius, Lunin and Stout

Noting the lack of a robust technique for estimating the age of foetuses and neonates the authors undertook this study in order to record and describe a number of histological criteria that would be useful in age estimation of cases in this group (Calonius et al., 1970). 92 cases from a number of sources were examined and histological sections of the jaws were taken. The age range was from 7 weeks inutero to 3 years following birth. The observations were divided into gross anatomical, developmental and topographical characteristics and were reported as such.

The authors described a timeline with specific histological features that could be observed at a given age. It was their intention that this information could then be used to estimate the age of an infant or foetus based on observation of these specific criteria and comparison to their documented timeline.

The main advantage of this system is that it covers an age bracket not covered by many of the other age estimation techniques. This feature also proves to be its greatest disadvantage. This very limited age range makes the technique inappropriate for many cases, and indeed this present study. Further, the destructive and time consuming nature of the requirement for histological sections also weighs heavily against the use of this technique.

6.3.9 Liliequist & Lundberg

Another widely used measure of maturity is that of skeletal age. The most widely used method available was described by Greulich and Pyle (Greulich and Pyle, 1959) and was based upon comparison of radiographs of the hand and wrist of an unknown case to that of the documented images taken for specific ages. This is what is commonly referred to as an 'atlas technique.' As with the dental charts of Schour and Massler the main flaw in this method is that the different bones (or teeth) may develop at different rates to each of the separate bones (or teeth) in the reference sample. With regard to dental age estimations, these circumstances often make it very difficult to match the radiograph of the unknown to one particular image and corresponding age from the reference sample. It was this problem that Liliequist and Lundberg set out to address (Liliequist and Lundberg, 1971).

The authors sought to determine whether or not the combination of methods of determining skeletal and dental maturity would give a more accurate estimate of chronological age than each method taken alone. The investigation was focused on two main parts. Firstly, assessing the reliability of The Schmid & Moll method of estimating age from analysis of the developing wrist bones (Schmid and Moll, 1960). Secondly, the authors sought to develop a means of estimating dental age with an associated numerical index that could be statistically processed. In this way the authors could measure a continuum of development as opposed to the specific age stages depicted in the reference images. These two methods were then combined and simplified, and the correlation between the two methods was assessed.

The sample consisted of 148 females and 139 males taken from a group of Swedish school children of varying socio-economic status. For the development of the dental-based system both intra and extra-oral radiographs were taken of each child. The development of the tooth was divided into eight stages, each stage being allocated a numerical score between 0 and 6. Each of the maxillary and all mandibular teeth (except third molars) were assessed from the radiographs and allocated a score based on the stage of development of each tooth. These scores were totalled to give a maturity score. The mean value and standard deviation of the scores for each tooth at each 1 year age bracket were computed, as was the mean value and standard deviation for the summed maturity scores.

This system may be used to estimate the chronological age of an individual based on the mean maturity scores for a given age bracket. The authors did not, however, state that this could be done. It was their intention that this system is well adapted for comparison of dental maturity between groups, as compared to estimating an absolute age. The advantages of this system are that: it recognises that a significant difference exists in the dental development rates of males and females, especially in the 8-12.5 year range – this allows for more accurate estimates of dental maturity; numerical values are given to the stages of development allowing for statistical analysis and easy comparison between groups; and importantly, the stages require relative measurements such as ‘root longer/shorter than crown’. These authors were one of the first groups to take this step, many others were to follow. As such, the correlation between observers was high (0.92-0.99) which indicates a system that is 'well adapted for reported comparative investigations by different observers' (Liliequist and Lundberg, 1971). However, the authors did not take into account the chance expected frequency of agreement between the observers in their study. Therefore this quoted figure is probably an overestimate of the true figure.

The authors found a strong correlation between left and right maxillary tooth development (r=0.99) and also between maxillary and mandibular tooth development (r=0.99), when maturity scores were summed. The authors concluded that an effective analysis could therefore be carried out on just one quadrant. This does simplify the method used.

The disadvantages of using this system to estimate age are two. Firstly, this was not the authors’ intent. Secondly, there is no differentiation between males and females despite the well published sexual dimorphism that exists. It is the latter point that may be a significant source of error in the application of this method.

6.3.10 Demirjian, Goldstein and Tanner

See next chapter for details.

6.3.11 Gustafson & Koch

In this study the authors sought to develop a schematic representation of tooth development based upon data collected from the literature (Gustafson and Koch, 1974). It was their intention that this diagram could then be used to estimate the age of an individual based on their degree of dental development, estimated from an OPG of a given subject.

The authors divided the process of tooth development into four stages:

I – commencement of mineralisation

II – completion of crown formation

III – tooth eruption/emergence

IV – completion of root formation

Data from nineteen separate articles was taken and reclassified according to the four stages described above. This information was then graphed according to the range of ages at which a given stage for a particular tooth was observed. By way of example, this chart is reproduced in Figure 6.6 below.

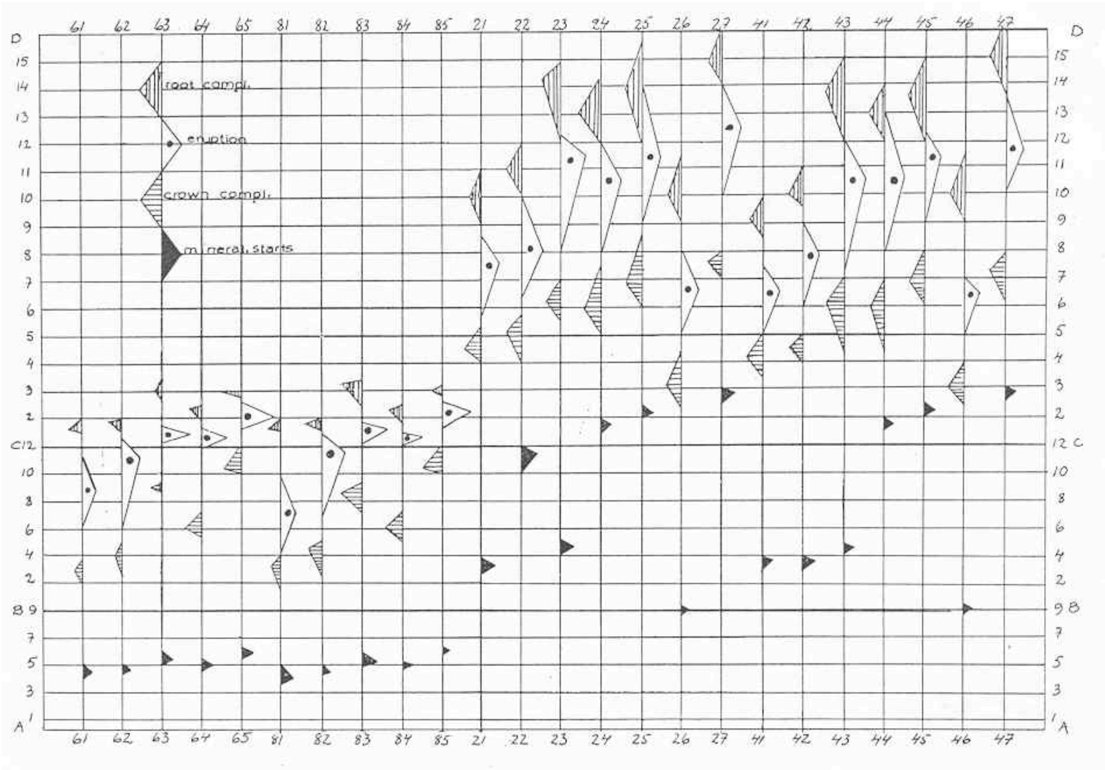


Figure 6.6: Schematic representation of tooth formation and eruption. A-B=intra-uterine life, B-C= first year of life, and C-D=2-16 years-of-age. The base of the triangle represents range and the peak mean age (from Gustafson and Koch, '74).

The development diagram was then tested using radiographs of 41 children aged 3-13 years. The reported accuracy for a single age estimation was ±4.97 months at the 95% confidence interval.

The obvious advantage of this system over some others is its simplicity in limiting the defined stages of development to four. One could infer that this would lead to greater inter/intra-observer agreement, however the authors did not address this aspect.

A flaw in this system is that it would appear almost impossible to assess a tooth as being at stage III - 'clinical emergence' - from nothing more than a radiograph. This is a point that the authors concede. The other main disadvantage of this system is that the process of using the diagram involves accurately identifying the stages of development of any/all teeth of the subject, estimating the age from one given tooth then varying this estimate intuitively based upon the stages of development of the other teeth. Finally it is important to note that this system, like many of the early systems, does not differentiate between males and females. Many studies have identified a significant sexual dimorphism in the rates of dental development (see section 6.2.3), and this may result in a significant source of error when not acknowledged.

6.3.12 Anderson, Thompson and Popovich

This study is yet another example of an researcher undertaking an investigation to ultimately provide a tool whereby the derived results can be applied to estimate chronological age from the degree of dental development. In this instance the authors sought to undertake a study far more extensive than those that preceded them, yet based on a methodology developed by those that had come before (Anderson et al., 1976). The system developed by Moorrees, Fanning and Hunt described fourteen morphologically distinct phases through which each developing tooth passes. Each of these stages is identifiable radiographically. The Anderson, Thompson and Popovich study sought to describe the mean ages of attainment (and standard deviation) of each of the fourteen stages of development described by Moorrees, Fanning and Hunt for every tooth in both dental arches, as assessed by examination of serial cephalograms of the sample population.

The sample consisted of 121 males and 111 females of Anglo-Saxon origin. An annual cephalogram was taken of each subject from 3 to 18 years-of-age. These radiographs were then analysed, with the stages of development for each tooth and the age of each subject at the time that the radiograph was taken being recorded. The mean ages of attainment (and standard deviation) for each stage, for each tooth was derived and the results recorded in tabular form, separated into male/female and mandibular/maxillary teeth. This table could then be used to estimate the chronological age of a subject based on the stages of development of the teeth of that subject. By way of example, only the results for the male mandibular teeth have been reproduced below in Table 6.2.

	Incisors						Premolars				Molars					
	Central		Lateral		Canine		First		Second		First		Second		Third	
Stage	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1									3.7	0.38			3.8	0.45	9.4	1.40
2									4.0	0.55			4.3	0.54	10.2	1.44
3									4.3	0.62			4.8	0.53	10.8	1.47
4					3.6	0.18	4.1	1.54	4.8	0.57	3.4	0.20	5.3	0.60	11.5	1.49
5			3.6	0.24	3.9	0.41	4.8	1.28	5.5	0.63	3.6	0.17	5.9	0.62	12.4	1.50
6	3.6	0.21	4.0	0.46	4.8	0.59	5.6	1.21	6.3	0.70	3.7	0.14	6.7	0.71	13.3	1.51
7	4.0	0.46	4.8	0.46	5.7	0.68	6.6	1.17	7.2	0.73	3.7	0.28	7.6	0.75	14.1	1.48
8	4.7	0.45	5.4	0.45	6.6	0.74	7.6	1.13	8.1	0.86	4.3	0.40	8.5	0.80	14.8	1.41
9	5.0	0.45	5.7	0.46	6.9	0.74	7.9	1.12	8.5	0.87	4.9	0.43	9.4	0.90	15.5	1.25
10	5.8	0.47	6.5	0.49	8.1	0.73	9.0	1.12	9.5	0.92	5.7	0.58	10.5	0.99	16.1	1.73
11	6.6	0.56	7.3	0.57	9.4	0.80	10.2	1.12	10.6	0.99	6.8	0.65	11.6	1.05	16.8	1.90
12	7.3	0.61	8.1	0.61	10.9	0.99	11.2	1.13	11.9	1.12	7.8	0.68	12.5	1.11	17.4	0.75
13	8.1	0.68	9.0	0.71	12.2	1.00	12.2	1.17	12.9	1.19	8.8	0.73	13.6	1.18	18.2	0.85
14	9.2	0.89	9.9	0.81	13.5	1.22	13.3	1.31	14.0	1.27	10.0	0.91	14.8	1.26	18.5	0.97

Table 6.2: Age (years) of attainment of mineralization stages of teeth of the male mandible (from Anderson, Thompson and Popovich, '76)

The advantage of this system is that, being based on all deciduous and permanent teeth, it is far more versatile than many derived in the previous studies. This versatility lies in the fact that any teeth can be used in the assessment. The clinician is not limited by the need for radiographs of specific teeth, which is the case with many systems, including that of Demirjian (Demirjian, 1976). This can be very useful from a clinical point of view in forensic cases when fragmentation, decomposition or predation of the remains may mean that not all teeth are actually recovered. The user may also use this versatility to their advantage by selecting teeth for analysis that have the least amount of variance about the mean, thus providing a more accurate age estimate. The system shares the same advantages as that of the system on which the study was based. Specifically; clearly defined stages, high intra-observer reliability, and applicability to both the deciduous and permanent dentition gives this system a wide age range of application.

As with the Moorrees, Fanning and Hunt study, the disadvantages are the same – the system relies on absolute measurements, has many stages with which the examiner needs to be familiarized, and is population specific. Another disadvantage is that this specific study does not cover the age range birth to three years, limiting its application in some fields. Finally, as only one assessor was used in this study, the consistency of assessment between observers remains unassessed. It would not, however, be unreasonable to consider the results of the Moorrees, Fanning and Hunt study as a reasonable estimation of inter-observer agreement when applying the methods described in this study.

6.3.13 Ciapparelli

This was a study similar in design to that of Anderson, Thompson and Popovich, in that it was based upon the stages defined by Moorrees, Fanning and Hunt, but it relied on data from OPGs instead of plain films. The author compared the results (mean age of attainment of each stage) to Moorrees and Anderson and found significant differences (Ciapparelli, 1985; Ciapparelli, 1992). By way of example the results for the mandibular second molar are reproduced below in Table 6.3

	Anderson et al. (1976)				Moorees et al. (1963)				Ciapparelli (1985)			
	Male		Female		Male		Female		Male		Female	
Mineralization stage	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
1	3.8	0.4	3.7	0.4	3.6	0.5	3.4	0.3				
2	4.2	0.5	4.2	0.5	3.9	0.4	3.5	0.5				
3	4.8	0.5	4.6	0.5	4.7	0.7	4.2	0.4				
4	5.3	0.6	5.1	0.6	5.1	0.5	4.8	0.5	6.1	0.4	5.8	0.1
5	5.9	0.7	5.6	0.6	5.6	0.6	5.3	0.6	7.2	0.5	6.5	0.4
6	6.7	0.8	6.3	0.7	6.4	0.7	6.3	0.7	7.4	0.9	6.8	0.6
7	7.6	0.8	7.1	0.7	7.1	0.6	7.0	0.8	8.3	1.7	7.9	0.6
8	8.5	0.9	8.1	0.8	7.8	0.8	7.8	0.9	9.1	0.9	8.7	0.5
9	9.5	0.9	9.0	0.8	9.1	1.0	9.0	1.0	9.7	0.9	9.4	1.2
10	10.6	1.0	10.0	0.9	9.9	1.1	9.8	1.0	10.4	1.6	9.9	1.4
11	11.5	1.1	11.0	0.9	10.6	1.3	10.4	1.2	11.7	1.0	11.6	0.7
12	12.4	1.2	11.8	1.0	11.3	1.1	11.0	1.3	12.0	1.1	11.9	1.7
13	13.4	1.3	12.6	1.1	12.1	1.3	12.2	1.1	13.9	1.1	13.8	1.3
14	14.6	1.3	13.6	1.3	14.4	1.3	14.1	1.5	15.6	1.0	14.9	0.9

Table 6.3: Comparison of dental development of mandibular second permanent molar using 14 stages of Moorrees et al. x (bar)= mean age, and SD= standard deviation (from Ciapparelli 92).

In his conclusion he infers that the differences in results of the three studies may be, at least in part, related to the fact that there are 'so many' stages to identify 'which may lead to debate in court as to where one stage begins and another ends' (Ciapparelli, 1992). This is at odds with self reported inter-observer error rate of Fanning of only 27% (Fanning, 1961). However, this figure may well be greater if the chance expected frequency of agreement had been taken into account as stated previously.

This study has the same systemic flaw that the Anderson study has; that is, mean age of attainment is not what is actually being assessed. The radiographs provide a snapshot in time of the stage of development of a given tooth or teeth. They do not necessarily capture the moment at which that stage is reached, except possibly by chance. In fact, the measure of mean age of attainment is actually the mean of all the ages for a given tooth that are classified as having reached one specific stage without having yet passed on to the next stage. While not truly a disadvantage of the system, the misnomer may lead to the misinterpretation of results when this system is used. Provided the clinician is aware of this fact, this system is no more or less reliable than those on which it was based.

6.3.14 Mörnstad, Staaf & Welander

The authors of this study sought to devise a system of age estimation based on the degree of dental development, while minimising the methodological variation inherent in so many other systems that are based on the subjective assessment of stages (Mörnstad et al., 1994b). To achieve this goal they tested the degree to which metric measurements of radiographic images of teeth correlated with true age. Finding a significant correlation the authors then developed a regression model to predict age from a given set of tooth measurements.

The study involved the examination of OPG radiographs of 270 male and 271 female children aged between 6 and 14 years. Each OPG was mounted on a digitising table and direct measurements taken under a crosshairs cursor. The measurements taken are detailed below in Figure 6.7.

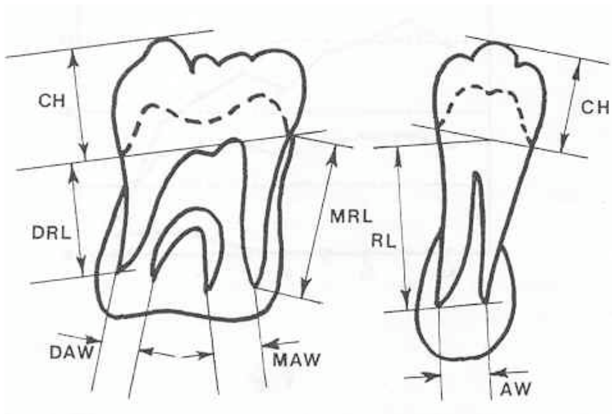


Figure 6.7: Distances measured between defined landmarks. CH, crown height. DRL, length of distal root in molars. MRL, length of mesial roots in molars. RL, root length of single-rooted teeth. DAW, width of distal apex in molars. MAW, width of mesial apex in molars. AW, width of apex of single-rooted teeth.

Overall the results yielded an R-square value of 0.78 with a standard error of estimate of about ±2 years at the 95% confidence interval. It was however, noted that the R-square value was as low as 0.45 for a given specific age group. A validation study by Liversidge found similar results, reporting mean error levels that were as low as 0.14 years for those aged under 8 years, to 2.25 years for those aged over 12 years (Liversidge et al., 1993).

The advantages of this methodology are that the measurements taken are absolute and objective, there is no room for subjective interpretation as there is in systems that require classification into a predefined category or stage. The measurements represent a continuous scale of development, not one that requires a subjective decision when classifying a tooth between one stage and the next. Finally the use of direct measurements means that little or no training is required for a clinician to accurately take the required measurements. Although not reported on, it is assumed that this last point would lead to a very high level of inter- and intra-examiner agreement.

The most obvious disadvantage of using this system is, like all previously reviewed systems, the lack of accuracy in the estimate of true age, especially in those specific groups whose predictive models had a low coefficient of determination values. The other main shortfall in this technique is the requirement to take absolute measurements from an OPG. While the authors attempted to compensate for magnification by dividing all results by a factor of 1.35, they have given no evidence to suggest that the magnification of teeth on any given OPG is consistent across the entire film. Nor have they given any evidence to suggest that the magnification of teeth on different OPGs is the same. If a consistent magnification between OPGs cannot be guaranteed, measurements cannot be accurately compared, nor can accurate estimations of age be calculated based on these measurements. This point alone was reason enough to not use this system in this present study. Finally, the need for a digitising table is a small but critical requirement of this technique and these can be costly.

6.3.15 Liversidge

Tooth length and weight have often been used to predict age in foetal and early post-natal growth, however little research has been done on the permanent dentition. The aim of this study was to build on the author's own earlier work (Liversidge et al., 1993), that had examined growth in tooth root length up to 5 years in age. In this later study the author sought to develop regression formulae to predict chronological age from tooth length in cases aged from birth to maturity (Liversidge and Molleson, 1999). Further aims were to compare direct and radiographic estimation of tooth length as well as assessing inter-observer error.

The cases used in this study were 76 individuals from an historical collection (18th century coffin buried juveniles with known age at time of death) – the Spitalfields Collection. The ages ranged from 1-19 years and while most of the sex in the sample was known, no differentiation between male and female was made due to the uneven distribution and small sample sizes. Radiographs were taken and teeth were dissected out to provide data on 354 teeth across the entire sample. Further inter-observer error was assessed on 100 teeth, as was the comparison of direct and radiographic measurement techniques.

Regression formulae for individual teeth were developed and these can be used to predict age based on measured tooth length. As the method is quantitative, minimal inter-observer error was measured. The authors also found that, provided the radiographs were unmagnified and undistorted, no significant difference between measurements made by either method existed. Therefore measurements could be made non-invasively using accurate radiographs. It is within these last few points that the true advantages of this method lie. That is; the method is non-invasive, simple and relies on a quantitative measure. As the method can use a single tooth in the estimations, it may prove very useful for remains where some teeth are missing, a stumbling block for many other methods.

The main disadvantage of this method is not so much in its design, but in its application. As the authors point out, it is essential for the regression to be based upon growth standards of an adequate number and on a relevant population, because, as with most methods of this type, population differences in rates of dental development mean a lack of universal applicability of the derived equations. Further, this study was based upon a small sample size where no differentiation was made between male and female and between maxillary and mandibular teeth. As the previously reviewed studies have revealed, significant differences exist in the rate and patterns of dental development between males and females. This may result in a potential source of error if not taken into account. Any possible differences between maxillary and mandibular tooth length and rate of development were not investigated in this study, leaving a potential source of error that should be investigated. Finally, the accuracy of the estimations may be over-estimated as the method involves reporting a simplified confidence interval based on the square root of the residual variance as a measure of standard deviation. In doing this the standard errors of estimate for all age groups will be averaged out over the entire age range, giving one consistent confidence interval. This may not reflect the true confidence intervals for any given age group, and may well underestimate them.

Chapter 7

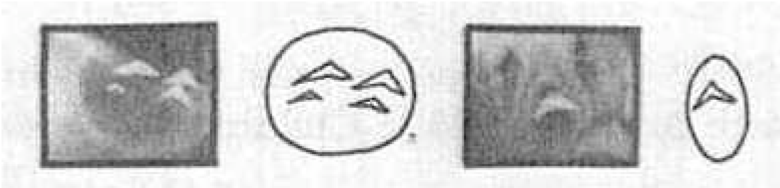
THE DEMIRJIAN SYSTEM

7.1 Description of the Demirjian System

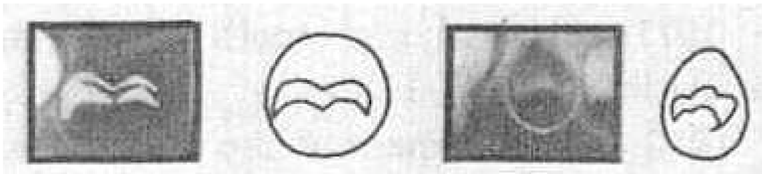
Following an extensive review of the literature, Demirjian, Goldstein and Tanner concluded that tooth formation was a more reliable indicator of dental age than tooth emergence. They sought to develop a method of estimating dental maturity using a numerical quantity based upon the stages of development observed in each tooth. It was the authors intent to develop centile charts that would allow conversion of the derived numerical 'maturity score' to dental age, and that this estimation could be used in the clinical and forensic settings to assess dental maturity and provide an estimate of chronological age (Demirjian et al., 1973).

The authors modified the defined system of stages previously published by Moorrees, Fanning and Hunt. They simplified this system by defining only eight stages of development. Further, the assessment of these stages relied on relative, not absolute measurements. The written descriptions of these stages were modified in a later paper by Demirjian in order to provide further clarification of the defining features of each stage (Demirjian, 1976). These stages and the updated descriptions are detailed in Figure 7.1 below.

A] In both uniradicular and multiradicular teeth, a beginning of calcification is seen at the superior level of the crypt in the form of an inverted cone or cones. There is no fusion of these calcified points.



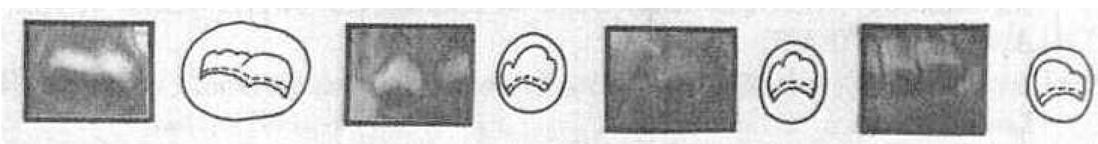
B] Fusion of the calcified points forms one or several cusps which unite to give a regularly outlined occlusal surface.



C] a. Enamel formation is complete at the occlusal surface. Its extension and convergence towards the cervical region is seen.

b. The beginning of a dentinal deposit is seen.

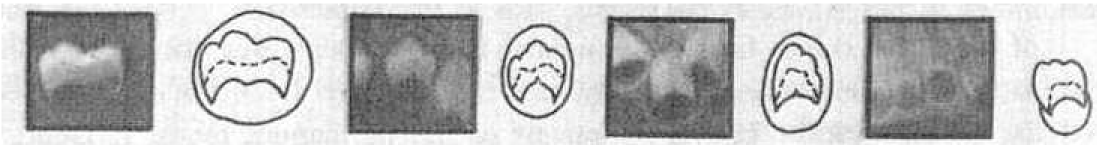
c. The outline of the pulp chamber has a curved shape at the occlusal border.



D] a. The crown formation is completed down to the cemento-enamel junction.

b. The superior border of the pulp chamber in the uniradicular teeth has a definite curved form, being concave towards the cervical region. The projection of the pulp horns if present, gives an outline shaped like an umbrella top. In molars the pulp chamber has a trapezoidal form.

c. Beginning of root formation is seen in the form of a spicule.



E] Uniradicular teeth:

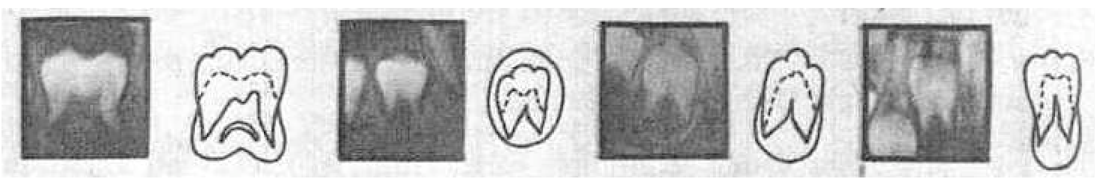
a. The walls of the pulp chamber now form straight lines, whose continuity is broken by the presence of the pulp horn, which is larger than in the previous stage.

b. The root length is less than the crown height.

Molars:

a. Initial formation of the radicular bifurcation is seen in the form of either a calcified point or a semi-lunar shape.

b. The root length is still less than the crown height.



F] Uniradicular teeth:

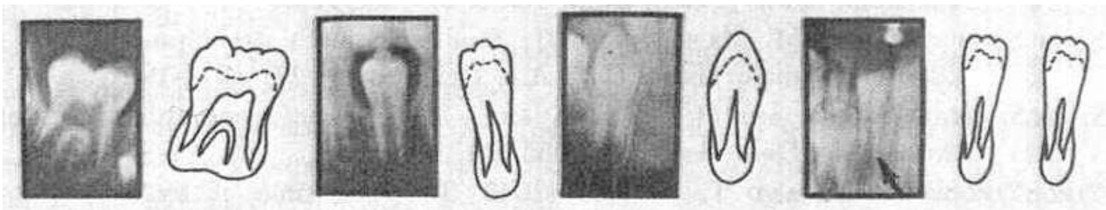
a. The walls of the pulp chamber now form a more or less isosceles triangle. The apex ends in a funnel shape.

b. The root length is equal to or greater than the crown height.

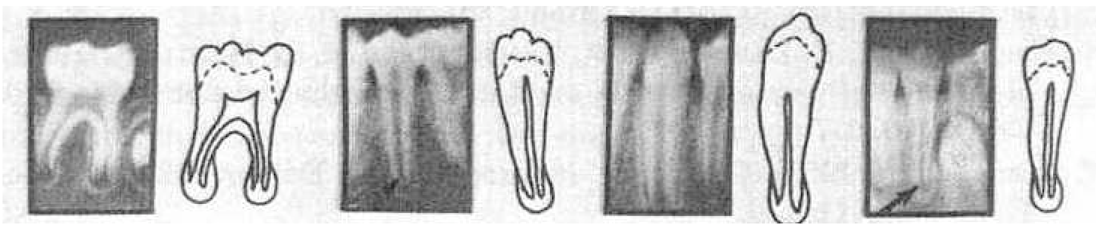
Molars:

a. The calcified region of the bifurcation has developed down further from its semi-lunar stage to give the roots a more definite and distinct outline with funnel shaped endings.

b. The root length is equal to or greater than the crown height.



G] The walls of the root canal are now parallel and its apical end is still partially open (Distal root on molars).



H] a. The apical end of the root canal is completely closed (Distal root on molars).

b. The periodontal membrane has a uniform width around the root and the apex.

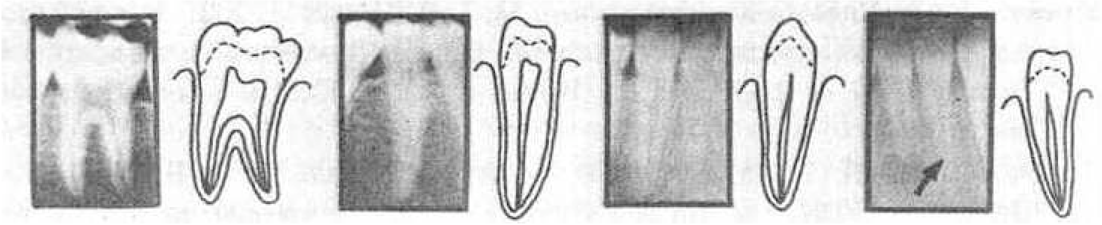


Figure 7.1: The development status of each group of teeth (from left to right - molars, premolars, canines, incisors) is defined for stages A-H. The definition of each stage of the permanent dentition is based on the associated biological criteria (from Demirjian '76).

In assigning ratings to the teeth as observed in the OPGs, Demirjian provided a set of rules as further guidance. These guidelines are:

1. The mandibular permanent teeth are rated in the following order: 2nd molar, 1st molar, 2nd bicuspid, canine, lateral incisor, central incisor.

2. All teeth are rated on a scale of A to H. The rating is assigned by following carefully the written criteria for each stage, and by comparing the tooth with the diagrams and x-ray pictures given. The illustrations should only be used as an aid, not as the sole source of comparison. For each stage there are one, two or three written criteria marked a), b), c). If only one criterion is given this must be met for the stage to be taken as reached; if two criteria are given, then it is sufficient if the first one of them is met for the stage to be recorded as reached; if three criteria are given, the first two of them must be met for the stage to be considered reached. At each stage, in

addition to the criteria for that stage, the criteria for the previous stage must be satisfied. In borderline cases the earlier stage is always assigned.

3. There are no absolute measurements to be taken. A pair of dividers is sufficient to compare the relative length (crown/root). To determine apex closure stages no magnifying glass is necessary. The ratings should be made with the naked eye.

4. The crown height is defined as being the maximum distance between the highest tip of the cusps and the cemento-enamel junction. When the buccal and lingual cusps are not at the same level, the midpoint between them is considered the highest point.

The sample used by Demirjian consisted of 1446 males and 1482 females of French-Canadian origin aged between 2 and 20 years. OPGs were taken of each case and the teeth 47 to 41 inclusive were assessed in terms of their developmental stage and assigned a rating of A to H (with 0 indicating calcification not yet commenced) in accordance with Figure 7.1 above.

The sample was split into males and females because of the widely reported prevalence of sexual dimorphism in dental development.

The authors chose the right mandibular teeth to study for a number of reasons. The choice of the mandibular over the maxillary teeth was one of practicality – bony structures of the maxilla often obstruct radiographic views of the permanent teeth, especially during the first 6 years of life. In the studies reviewed above, many have limited their research to the mandibular teeth for this same reason (Liliequist and Lundberg, 1971; Moorrees et al., 1963a; Nolla, 1960). Conversely the teeth of the mandible are quite clearly visible in an OPG, with the possible exception of older type OPGs where the cervical spine became superimposed over the mandibular anterior teeth. Regarding the decision to only use teeth from one side of the mandible, several researchers have demonstrated a very high correlation between the developmental stages of the teeth of the left and right sides of the maxilla and mandible (Anderson et al., 1976; Green and Aszkler, 1970; Koshy, 1998; Mörnstad et al., 1994b; Pelsmaekers et al., 1997).

The assigned ratings (0-H) were analysed and were used to develop the next stage of the study. This was a further modification to this system based on the work of Tanner, Whitehouse, and Healy who developed an approach to age estimation based on skeletal maturity whereby each bone was given a weighted numerical score (Tanner et al., 1962). A modification of part of this method was used to derive what Demirjian referred to as 'self-weighted' numerical values for each stage of each tooth, the author differentiating between male and female. These figures were later reviewed and updated by Demirjian in a subsequent study (Demirjian, 1976) and are as follows:

MALE	Tooth number						
Rating	47	46	45	44	43	42	41
0	0		0				
A	1.7		1.5	0			
B	3.1		2.7	4			
C	5.4	0	5.2	6.3	0	0	0
D	8.6	5.3	8	9.4	4	2.8	4.3
E	11.4	7.5	10.8	13.2	7.8	5.4	6.3
F	12.4	10.3	12	14.9	10.1	7.7	8.2
G	12.8	13.9	12.5	15.5	11.4	10.5	11.2
H	13.6	16.8	13.2	16.1	12	13.2	15.1

Table 7.1: Conversion table – self-weighted scores for Dental Stages – male (from Demirjian 1976)

FEMALE	Tooth number						
Rating	47	46	45	44	43	42	41
0	0		0				
A	1.8		1.7	0			
B	3.1		2.9	3.1			
C	5.4	0	5.4	5.2	0	0	0
D	9	3.5	8.6	8.8	3.7	2.8	4.4
E	11.7	5.6	11.1	12.6	7.3	5.3	6.3
F	12.8	8.4	12.3	14.3	10	8.1	8.5
G	13.2	12.5	12.8	14.9	11.8	11.2	12
H	13.8	15.4	13.3	15.5	12.5	13.8	15.8

Table 7.2: Conversion table – self-weighted scores for Dental Stages – female (from Demirjian 1976)

For each case analysed Demirjian then converted the attributed stage for each tooth to a self-weighted numerical score based on the above Tables 7.1 and 7.2. For example, if the tooth 47 of a male was assessed as being at stage A, this would be converted to a score of 1.7; similarly, the tooth 47 of a female assessed as being stage A would be converted to a score of 1.8. This conversion gives a set of tooth scores for each case, the sum of which results in a summative 'Maturity Score' for that case. Centile charts for both males and females were then derived that allowed for conversion of this total maturity score to dental age. For the purposes of this present Sydney study, the 50th centile curves from these charts were converted to a numerical table:

Female Demirjian Maturity Score	Male Demirjian Maturity Score	Age (years)	Female Demirjian Maturity Score	Male Demirjian Maturity Score	Age (years)	Female Demirjian Maturity Score	Male Demirjian Maturity Score	Age (years)
11.5	11.9	2.6	60.7	53	7	96	94.2	11.4
12.4	12.7	2.7	62.8	54.9	7.1	96.2	94.5	11.5
13.4	13.5	2.8	65.3	56.2	7.2	96.3	94.8	11.6
14.1	14.3	2.9	66.9	57.8	7.3	96.6	95	11.7
15	15	3	68.9	59.3	7.4	96.8	95.2	11.8
16.1	16	3.1	70.4	61.1	7.5	96.9	95.5	11.9
16.9	16.9	3.2	72	63.3	7.6	97	95.7	12
17.8	17.5	3.3	73.5	65.5	7.7	97.1	96	12.1
18.6	18.2	3.4	74.9	67.5	7.8	97.3	96.2	12.2
19.7	19.2	3.5	75.9	69.4	7.9	97.4	96.4	12.3
20.6	20.1	3.6	77.1	71.3	8	97.6	96.6	12.4
21.3	21	3.7	78.2	73	8.1	97.8	96.7	12.5
22.2	21.9	3.8	79.2	74.5	8.2	97.8	96.9	12.6
22.9	22.7	3.9	80	76	8.3	98	97	12.7
24	23.5	4	81.2	77.1	8.4	98.1	97.1	12.8
25.1	24.7	4.1	81.9	78.2	8.5	98.2	97.3	12.9
25.9	25.3	4.2	82.6	79.3	8.6	98.3	97.5	13
26.6	26.1	4.3	83.3	80.1	8.7	98.4	97.6	13.1
27.3	27	4.4	84.2	81	8.8	98.5	97.8	13.2
28.1	28	4.5	84.8	81.8	8.9	98.7	97.9	13.3
29.5	29.2	4.6	85.4	82.7	9	98.8	98	13.4
30.1	29.9	4.7	86.2	83.2	9.1	98.8	98.1	13.5
31	30.8	4.8	86.9	84	9.2	98.9	98.2	13.6
31.9	31.4	4.9	87.5	84.7	9.3	98.9	98.3	13.7
32.7	32.1	5	88	85.2	9.4	99	98.4	13.8
33.9	33.2	5.1	88.6	85.9	9.5	99	98.5	13.9
34.9	34.3	5.2	89.2	86.6	9.6	99.1	98.6	14
35.9	35.2	5.3	89.7	87	9.7	99.1	98.7	14.1
37	35.9	5.4	90.1	87.6	9.8	99.2	98.8	14.2
38.1	36.8	5.5	90.7	88.2	9.9	99.3	98.9	14.3
39.4	37.9	5.6	91.2	88.7	10	99.4	99	14.4
40.6	38.9	5.7	91.8	89	10.1	99.4	99.1	14.5
42	39.8	5.8	92.1	89.5	10.2	99.5	99.2	14.6
43.2	40.7	5.9	92.6	90	10.3	99.5	99.2	14.7
44.5	41.7	6	93	90.4	10.4	99.6	99.3	14.8
46.2	43	6.1	93.3	90.8	10.5	99.7	99.3	14.9
47.7	44.1	6.2	93.7	91.5	10.6	99.7	99.4	15
49.1	45.2	6.3	94.1	91.9	10.7	99.8	99.4	15.1
50.3	46.1	6.4	94.4	92.2	10.8	99.8	99.5	15.2
52.1	47.4	6.5	94.7	92.6	10.9	99.8	99.6	15.3
53.7	48.7	6.6	94.9	92.9	11	99.9	99.7	15.4
55.3	49.9	6.7	95.2	93.2	11.1	99.9	99.8	15.5
57.2	51	6.8	95.5	93.6	11.2		99.8	15.6
59	52.1	6.9	95.8	94	11.3		99.8	15.7

Table 7.3: Conversion table – Demirjian Maturity Score to Dental age – male & female (from Demirjian 1976)

By way of example, if the Demirjian Maturity Score for a female case was 11.5, then their estimated age would be 2.6 years. It was the authors' intent that this method would be used to estimate the age of a case by taking the following steps: (1) assign each tooth 47-41 a rating using the above descriptions, (2) convert this rating to a Demirjian maturity score using the above tables and finally (3) estimate the age of the individual using the conversion charts.

The advantages of this method are that the system of Moorrees, Fanning and Hunt has been simplified to fewer stages that rely on relative, not absolute, measurement. Further, the stages are described in detail with reference diagrams and radiographs depicting each stage for each tooth type. This provides a system that would appear accurate, yet simpler to use than its predecessors, thus one would expect a higher degree of inter-examiner agreement. The reported variability between observers was given as 'less than 10% of films showed any disagreement in analysis and never by more than 1 stage'. Unfortunately the format of this reported disagreement does not allow for direct comparison to the previously described methods.

Another common difficulty in comparing differing methods of age estimation is related to the number of defined stages. While a ‘coarser grading’, of say four stages, may lead to a higher agreement, the overall accuracy of the age prediction must also be taken into account when assessing the method. The reverse is also true, a more accurate prediction of age that may be gained using a ‘fine grading’ of many stages is not of much use if the system is not reliable. In support of this statement, Kullman found that using a method with stages of a ‘fine grading’, whereby seven stages that only related to root formation were used, a level of inter-observer agreement of only 57% was recorded (Kullman, 1996). The choice of eight stages by Demirjian appears to be the middle ground - a good compromise between system accuracy and reliability.

The first obvious disadvantage of the Demirjian system is that one requires all seven mandibular teeth to make an assessment. In forensic cases involving trauma, decomposition, skeletonisation, or predation, teeth are often missing, while in other cases the teeth may be missing due to caries or agenesis. While the authors have suggested substituting an assessment of the matching tooth from the contra-lateral side in such cases this is not always possible. The author attempted to address this issue in a later study that sought to limit the basis of the system to four, not seven, mandibular teeth (Demirjian, 1976). The graphed results of this later study appeared to produce a less accurate estimation of age. A further minor disadvantage of this 7-tooth system is the need for either an OPG or a full quadrant set of periapical radiographs to be taken. In a forensic setting, OPGs are often very difficult to take effectively, if at all. In such cases, the forensic odontologist would rely on periapical radiographs. As with other methods based on staging criteria, the level of reliability of the system is dependent on the examiner's level of familiarity with the detail of the stages. This shortcoming has been addressed, in part, by the author with the production of reference sample radiographs, line drawings and precise definitions of each stage as well as the provision of a training package to familiarise the examiner with the system – essentially a pre-calibration exercise. The age bracket of approximately 2-15 years also limits the system in its applicability. Finally, and most importantly, the predictive centile curves of this study are population specific. While they may work well on cases of

French-Canadian origin they will routinely over- or under-estimate predicted age of cases of a genetically different heritage. The author recognised this shortcoming and recommended that population specific conversion tables be developed for use in other regions.

As stated earlier, approximately three years after their original study, the authors sought to improve upon their system. The revised system could use just four teeth as described above, but more importantly, they supplied revised self-weighted scores for each stage of each tooth for each sex (Demirjian, 1976). These scores apparently provided a more accurate prediction of age for the reference sample. It is these self-weighted scores and the associated conversion charts detailed in Tables 7.1, 7.2 and 7.3 above, for converting the summative maturity score to dental age, that were used in this study.

7.2 Validation Studies of the Demirjian System

The Demirjian system has been used in many other studies to assess population variability in dental development (see section 6.2.1.1). As was the case in many of these studies, a level of validation and review of this system was undertaken. While Demirjian reported a range of up to 3 years between the 3rd and 97th percentile (Demirjian et al., 1973), Haag and Matsson found the predicted ages were associated with a 95% confidence interval of ± 2 years (Hägg and Matsson, 1985). Similar results were reported by other authors (Davis and Häag, 1994; Nykanen et al., 1998; Staaf et al., 1991;

Chaillet et al., 2004). Kataja found the Demirjian system was most effective in the 5-10 year age range, then went on to develop prediction curves based on the Finnish population for use in later studies (Kataja, 1989). This last step by Kataja is a common approach to modifying the Demirjian system for use on differing populations. While most authors have relied on Demirjian's published self-weighted scores, the recent study by Chaillet et al. used software based on Goldstein's original method (Healy and Goldstein, 1976) as used by Demirjian (Demirjian, et al., 1973) to derive population specific self-weighted scores. Chaillet et al. found that this method was far more accurate than using Demirjian's original self-weighted scores and centile charts. The regression formula derived by Chaillet et al., based on their population specific self-weighted scores, provided age estimates with a prediction error of ± 2.3 years at the 97% confidence level for ages 2 to 16 years. These results are similar to those reported by other authors, reviewed earlier in this section, who did not derive population specific self-weighted scores but used Demirjian's published scores

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Other authors have undertaken studies on the reliability of the Demirjian system such as Haag, however the presentation of their results does not allow for easy comparison to the present or other studies (Hägg and Matsson, 1985). In the Haag study, the results were expressed as the mean differences in estimates of age and while the reported mean difference of 0.6 years was not statistically significant it is hard to make a comparison to the other studies.

In another study, Haag and Matsson found that (with the use of pre-calibration training) intra-observer error resulted in mean differences in predicted age of up to 1.4 months and between observers of up to only 0.6 months (Hägg and Matsson, 1985). Staaf et al. found that the intra-observer error resulted in a mean difference in estimations of 0.4 months which was not found to be significant (Staaf et al., 1991). Nykänen et al. and Liversidge et al. all reported intra-observer agreement to be at about 86%, the former reporting an inter-observer error of 78% (Liversidge et al., 1999; Nykanen et al., 1998). These figures are very similar to those presented by Demirjian and Levesque (Demirjian and Levesque, 1980; Levesque and Demirjian, 1980). A number of studies by Nyström produced results for intra-observer agreement varying between 86% and 94% (Nyström, 1986; Nyström, 1988; Nyström et al., 2000). These results were similar to those reported by Frucht et al. who found intra-observer agreement levels of 93% (Frucht et al., 2000). Nyström also found far higher levels of agreement when pre-calibration of the examiners was undertaken, a result consistent with many other studies. (Davis and Häag, 1994; Kullman, 1996; Nyström, 1988; Thorson and Häag, 1991).

In concluding the Lévesque and Demirjian 1980 study the authors suggested a number of steps to take in order to maximize the level of agreement. They recommended the use of reference radiographs and precise word definitions of the stages to be identified, that analyses should be cross-checked by another examiner and they emphasized the need for examiner familiarity with the system. Thorsoon and Haag corroborated these sentiments in their study in which they found that they could reduce the level of inter-observer disagreement to a negligible amount by ‘pre-calibrating’ the examiners (Thorson and Häag, 1991). This concept has been further supported by Cockshott who, in a study on skeletal ageing, found that the level of experience of the observer affects the standard of performance and hence reliability of the system (Cockshott and Park, 1983). He suggested that training helps to ensure consistent results. In the Kullman study, he too found that especially where subjective assessments are to be made, pre-calibration of the observer would have a positive influence on reliability of the results (Kullman et al., 1996).

To aid in the pre-calibration process, and so enhance the examiners' familiarity with his system, Demirjian designed and released a training package. This package consisted of a series of reference radiographs, detailed descriptions of the stages and a training program to allow examiners to become familiar with the system prior to its implementation. This package is available on CD-ROM and was used in this present study for not only pre-calibration but also as a reference during assessments in an attempt to maximise both inter- and intra-observer agreement.

Chapter 8

Materials & Method

8.1 MATERIALS

The materials for this study were obtained from five dental clinics selected in different locations across the Sydney region. They were (then) Westmead Dental Hospital; (then) United Dental Hospital (Surry Hills); Dee Why School Dental Clinic; Daceyville School Dental Clinic; and Marrickville School Dental Clinic. From each of these clinics a list of patients under the age of 19 was obtained. The entire list of patients was used to gain the number of cases used in this present study.

In total, 3261 cases were selected, consisting of 1623 females and 1638 males, aged between 1 and 23 years. The racial background of each case was unknown. Table 8.1 below details the final number of cases used for this study, sorted by location.

Location	Number of Cases (Female)		Number of Cases (Male)		Total	
	n	%	n	%	n	%
Westmead	1453	44.6	1469	45.0	2922	89.6
Dee Why	115	3.5	110	3.4	225	6.9
United Dental Hospital	16	0.5	26	0.8	42	1.3
Daceyville	29	0.9	12	0.4	41	1.3
Marrickville	11	0.3	20	0.6	31	0.9
Totals	1624	49.8	1637	50.2	3261	100.0

Table 8.1: Distribution of cases analysed by location

The files on the selected cases were obtained and an OPG, if present, was temporarily removed from the file for analysis.

Following the acquisition of the available records a number were excluded. The reasons for these exclusions were divided into three main areas, technical, patient factors, and incomplete information. The technical reasons for exclusion were based on the quality of the OPG films, and included:

- Image distortion due to either patient movement during exposure, or malposition of patient for exposure;
- Incomplete image formation due to incorrect exposure technique; and
- Lack of image clarity due to under- or over-exposure, or under or over-development of the film.

Cases were excluded from this Sydney study if the patients had any:

- Significant numbers of missing teeth due to disease or trauma;
- History of chronic disease, illness or syndrome known to significantly affect dental development; or
- History of medical treatment known to significantly affect dental development.

Finally, cases were excluded if the files did not contain the required information. Most commonly, this included missing:

- Radiographs,
- Patient details such as date of birth, and
- Treatment details such as date of exposure of radiograph.

Table 8.2 below details the final numbers of cases sorted by age group. For the purposes of simplification in this study each age group is referred to by its mid-point e.g. 3.5 - 4.4 is the '4 year-olds' group.

YEARS	FEMALE		MALE		TOTAL	
	n	%	n	%	n	%
0-2.4	37	1.1	62	1.9	99	3.0
2.5-3.4	90	2.8	114	3.5	204	6.3
3.5-4.4	107	3.3	106	3.3	213	6.5
4.5-5.4	109	3.3	123	3.8	232	7.1
5.5-6.4	86	2.6	80	2.5	166	5.1
6.5-7.4	103	3.2	118	3.6	221	6.8
7.5-8.4	101	3.1	117	3.6	218	6.7
8.5-9.4	103	3.2	150	4.6	253	7.8
9.5-10.4	114	3.5	140	4.3	254	7.8
10.5-11.4	92	2.8	110	3.4	202	6.2
11.5-12.4	102	3.1	83	2.5	185	5.7
12.5-13.4	86	2.6	66	2.0	152	4.7
13.5-14.4	85	2.6	76	2.3	161	4.9
14.5-15.4	81	2.5	65	2.0	146	4.5
15.5-16.4	89	2.7	62	1.9	151	4.6
16.5-17.4	74	2.3	42	1.3	116	3.6
17.5-18.4	54	1.7	50	1.5	104	3.2
18.5-19.4	57	1.7	34	1.0	91	2.8
19.5-20.4	36	1.1	27	0.8	63	1.9
20.5-21.4	13	0.4	12	0.4	25	0.8
21.5-22.4	3	0.1	0	0.0	3	0.1
22.5-23.4	1	0.0	1	0.0	2	0.1
TOTAL	1623	49.8	1638	50.2	3261	100

Table 8.2: Distribution of cases analysed by age group and sex

8.2 METHOD

The stage of development was assessed by the Demirjian System and by the system of Schour and Massler. Age determination of the sample material was assessed according to these systems, and by two alternative systems: the first based on the use of the self-weighted scores published by Demirjian to derive a Demirjian maturity score (DMS); and the second based on the stages described by Demirjian, using a different weighting to derive what is referred to as simple maturity score (SMS). Both DMS and SMS were separately regressed against the true age of each case to derive age predictive formulae.

8.2.1 DATA COLLECTION

DEMIRJIAN SYSTEM

8.2.1.1 Pre-calibration of Examiner

In order to ensure the uniformity with which the analysis was undertaken, a training package developed by Demirjian was used by the author. The training was CD-ROM based. The user was presented with a random selection of OPG images where it was the purpose to rate the teeth of the 4th quadrant according to the stages defined by Demirjian (detailed previously). Each training session allowed for the user to analyse and assign ratings to just over 300 individual teeth. After each tooth was assessed, the correct answer, according to Demirjian was given. A tally of correct answers along with the total number of teeth analysed was given at the end of each training session. The author undertook upward of ten separate training sessions prior to commencing the study, and a further ten each time a significant time had elapsed between sessions of OPG analysis. All ‘pre-calibration’ training sessions on the training software resulted in agreement of scores in 82-87% of all assessments.

8.2.1.2 Assessment of Attained Stages of Development

Each OPG was taken and placed on a radiograph viewing box and was then correctly oriented. The fourth quadrant, the mandibular right hand side was the focus for the analysis. Each tooth in the 4^{th} quadrant was examined in turn and compared to the stages of development as described by Demirjian (Demirjian, 1976). For guidance these stages are described both in written and pictorial form and have been detailed in the previous chapter.

Once the stage that most accurately described the state of development of the tooth in question was identified, that alpha-numeric rating was assigned to that tooth and recorded in the appropriate box on the data sheet. The process was repeated for each of the teeth 47 to 41. The assigned ratings for each of the seven teeth were recorded on the data sheet for that specific OPG along with the unique identifier for each case, their sex, date of birth and date of OPG exposure. An example of the data sheet is contained in Appendix A1.

While the author undertook the majority of the analysis, it is important to note that approximately 800 OPGs were examined and graded by Dr N. Andrews. Dr Andrews is a Visiting Dental Officer at Westmead Dental Hospital, Westmead Forensic Dental Unit and also at the NSW Department of Forensic

Medicine, Glebe. As such, an analysis of inter-observer error was also undertaken, the details of which are described in a later section.

8.2.1.3 Assessment of Inter-Observer Error

To assess the degree of inter-observer error a random sample of 74 OPGs was selected from those previously analysed by Dr N. Andrews and reanalysed by the author by the same method described above. The two sets of results for each case were then compared and the number and amplitude of discrepancies by case and by tooth number were recorded under the appropriate case.

The degree of inter-observer variability, or more precisely the level of agreement or consistency between observers, was assessed using the Kappa statistic. The following formula was used:

$$K=(P_o-P_e)/(1-P_e)$$

where P_o is the observed proportion of agreement and P_e is the proportion of agreement that is expected due to chance alone (Landis and Koch, 1977). Kappa provides a far more reliable indication of the level of agreement between observers than simply looking at the proportion of times that two observers' analyses are consistent (P_o) because it takes into account and negates that proportion of agreement between them that is chance-expected. A high Kappa value indicates a high degree of consistency between observers and therefore implies a low level on inter-observer error and, as such, a reliable reproducible scoring system. According to Landis and Koch the following values for Kappa represent the respective degrees of reliability of consistency/agreement between observers:

Kappa value	Degree of Reliability
<0	Poor
0 – 0.2	Slight
0.21 – 0.4	Fair
0.41 – 0.6	Moderate
0.61 – 0.8	Substantial
0.81 – 1.0	Almost Perfect

Table 8.3: Kappa values and their associated degree of reliability (from Landis and Koch 1977)

The Kappa statistic was calculated for the overall analysis and then for the analysis by individual tooth type. This was done to show whether or not the assessment of any particular tooth type was more or less consistent than the others, indicating any teeth types that may have been difficult to assess consistently. Similarly the kappa values were then calculated for each development stage (0-H) in the overall analysis. To do this the assessments of each stage had to be dichotomised into, for example A and NOT A. This was done so as to show whether or not any one particular stage was more or less likely to be consistently assessed. This process was then repeated for each developmental stage for each individual tooth type.

8.2.1.4 Assessment of Intra-Observer Error

To assess the degree of intra-observer error a random sample of 181 OPGs was selected from those previously analysed by the author. These were reanalysed as described above, approximately 2 years after the initial analysis was undertaken. The two sets of results for each case were then compared and the number and amplitude of discrepancies by case and by tooth number were recorded under the appropriate case, and the kappa statistic was calculated.

8.2.1.5 Conversion of Assessed Stages of Development to Demirjian Maturity Score (DMS)

The raw alpha-numeric stages 0 to H, as assessed and recorded for each tooth in each case in the entire sample, were converted to a numerical score (where they are referred to as self-weighted scores). This was done using the sex specific tables constructed by Demirjian and detailed in Tables 7.1 and 7.2 in the previous chapter.

The individual self-weighted scores for a given case were then totalled to give that case a 'Demirjian Maturity Score' (DMS).

8.2.1.6 Conversion of Assessed Stages of Development to Simple Maturity Score (SMS)

A simpler numerical scoring system was assigned to each stage of each tooth. The raw alpha-numeric stages 0 to H, as assessed and recorded for each tooth in each case in the entire sample were also converted to a numerical maturity score (see Table 8.4).

Demirjian Rating	Maturity score
0	0
A	1
B	2
C	3
D	4
E	5
F	6
G	7
H	8

Table 8.4: Conversion table – alpha-numeric stage to maturity score (after Demirjian 1976)

By way of example, any tooth assessed as being at stage A will receive a score of 1. The individual tooth maturity scores for a given case were then totalled to give a case score referred to as the 'Simple Maturity Score' (SMS).

8.2.1.7 Mean Ages of Scores

Age-specific mean SMS were calculated. The minimum and maximum of these scores was also noted to give a better indication of range of natural variation in the sample. T-tests were conducted to ascertain the significance, or otherwise, of any sex differences.

SCHOUR AND MASSLER SYSTEM

8.2.1.8 Schour and Massler Method of Estimation of Age

At this time an estimation of the patients age was made using the method devised by Schour and Massler (Schour and Massler, 1941). The reason for the inclusion of this method is that it is occasionally used at the NSWDOFM, and a comparison of its accuracy has not previously been undertaken on a

Sydney sample. This method, reviewed in the previous chapter is based on the atlas approach to age estimation. The chart that Schour and Massler devised, contains pictorial representations of the state of dental development that can be expected for an individual at a given age and is reproduced in the review of this method in Section 6.3.2. Each OPG was compared to the visual descriptions in the Schour and Massler chart and the associated age of the stage that best matched that observed in the OPG was recorded on the respective data sheet. In cases that were borderline between two depicted age brackets an estimated age of x.5 was assigned, with x being the earlier age. It should be noted however, that for a number of mainly logistical reasons, not all OPGs had this assessment undertaken on them.

Once all information was recorded the data sheets were collected and stored for later analysis. At that time the data were transferred to Microsoft Excel spreadsheets.

8.2.2 DATA ANALYSIS

The first purpose of the analysis was to test whether the Demirjian system was able to predict ages in the Australian sample. However, since the Demirjian system is based on a assigning development stages and of weighting each stage as part of a process for arriving at a development score, it was anticipated that the predicted ages would not match those of the Australian sample, because the weighting system and age estimation curves used by Demirjian was derived from a Canadian sample.

Therefore, a second purpose of the analysis was to test two alternative approaches based on the Demirjian system. Both alternatives were based on of assigning the Demirjian developmental stages. The first alternative approach then used the Demirjian self-weighted scores, and a case score referred to as the Demirjian Maturity Score (DMS) was calculated. Age estimation equations based on the Australian sample using DMS were then derived by regression. The second alternative approach did not use Demirjian's system of self-weighted scores. Instead, the weightings used, corresponding to the eight development stages are given in Table 8.4 and a case score, referred to as the Simple Maturity Score (SMS) was calculated. Age estimation equations based on the Australian sample using SMS were then derived by regression.

For the purpose of evaluating the alternative approaches, they were developed on one third of the total sample (referred to as the development sample) and then tested on the remaining two-thirds (validation sample). Upon selection of the final models, the sample was recombined and the regression equations were recalculated on this larger sample.

8.2.2.1 Calculation of Chronological Age (CA)

A function of Microsoft Excel was used to calculate the difference between the recorded date of birth and the date that the OPG was taken, thus giving the chronological age of the patient at the time of the radiograph. This was then recorded on the spreadsheet as 'Chronological Age' under the appropriate case.

8.2.2.2 The Development and Validation Samples

At this stage the sample cases were randomly divided into a $^{1}/_{3}$: $^{2}/_{3}$ split using a random key generated by the RND function of Microsoft Excel. One group, labelled the 'development sample' consisted of 1086 individuals (549 male, 537 female) and the other group labelled the 'validation sample' consisted of 2175 individuals (1089 male, 1086 female).

8.2.2.3 Age Estimates According to the Demirjian System

In order to assess the precision of the Demirjian system to predict ages in this Australian sample, it was applied to the development sample. Predicted age (according to the Demirjian charts) was compared with true age, and deviations were calculated.

The estimate of age, referred to as 'Canadian Predicted Age' (CPA) was compared with the actual age for each case to measure the magnitude of the overestimates or 'prediction errors.' The mean overestimates for each age group and overall were then calculated. A t-test was undertaken to ascertain the significance, or otherwise, of the magnitude of the prediction errors.

8.2.2.4 Age Estimates According to Alternative Models

Actual age of subjects in the development sample was plotted against DMS and regression analyses were carried out. The resultant regression equation indicated predicted age. This equation was then applied to the validation sample, and deviations between actual and predicted ages were calculated. This entire process was then repeated using SMS in place of DMS.

a) REGRESSION ANALYSIS

Regression analysis was used to capture the function between DMS and chronological age, ultimately for the purpose of predicting chronological age from a known DMS. Using the development sample, the relationship between the calculated values of DMS and chronological age was assessed statistically with multiple regression analysis using the least squares method. As such, chronological age was regressed on DMS for each sex individually. The additional variables, in this study the DMS multiplied to varying powers, were introduced as predictors into the model one at a time. The number of powered predictors did not exceed 5 (i.e. DMS^5). All models were fitted to the data set, and the final 'preferred models' selected. The criteria for selecting the final models were: (a) the powered predictors used were to the highest power, where (b) all predictors were jointly significant. In this present study the use of these criteria provided models with the highest value for the coefficient of determination (R-square), i.e. the model in which the proportion of variation in predicted age that is explained by the variation in the DMS is maximised. In the case of having more than one independent variable R-square is adjusted to allow for a reduction in the degrees of freedom and is referred to as the adjusted R-square. In this paper all R-square values have been adjusted where required.

The predictors were introduced into the regression model one at a time. After each addition a t-test and F test were undertaken. The t-test was undertaken to establish if the regression coefficients were each statistically significant when all other terms were held constant. The F-test was undertaken on each regression model in order to confirm that, in the overall equation describing the correlation between predicted age and DMS, all predictors are jointly statistically significant.

The process was then repeated for the next powered predictor and so on. Additional regressions were carried out on modified samples when the upper limits of the DMS were truncated to the score of 99.5 for females and 99.2 for males. That is to say that any case when the DMS was greater than the given maximum score was considered outside the scope of the model and disregarded. These cut-off points were selected as, using the self-weighted scores of Demirjian, they represent the penultimate possible DMS for each sex. Any further truncation of scores would have resulted in a model with too limited an age range.

Next, the entire regression process was then repeated for the scores on the developmental sample that had been converted to the Simple Maturity Score (SMS) earlier on. As with the previous round, additional regressions were carried out on modified samples whereby the upper limits of the SMS were truncated to the score of 55. This figure was selected as it represents the penultimate possible SMS for each sex. Any further truncation of the sample would have resulted in too limited an age range, as described above, and was therefore not pursued in this present study.

The data analysis package in Microsoft Excel was used for these calculations.

For each sex, the preferred regression models were selected using the criteria detailed earlier in the Methods section. In addition, the same criteria were used to select the preferred models for the truncated samples using both the DMS and SMS. When examining the truncated models one additional criteria was considered, that being the age range covered by the models. All else being equal, the greater the age range, the more useful the model.

Models, based on data whereby the high-end scores were disregarded prior to regression, provided slightly higher coefficients of determination than those based on the full data set. These models were included for further examination despite the fact that they generated a reduced range of age estimates.

b) TEST OF PREDICTIVE MODELS

Calculation of Predicted Age (PA) Using Selected Regression Models

Using the calculated SMS and DMS data as appropriate, each of the above selected regression formulae were used to derive predicted ages for each case in the validation sample. This estimate of age, referred to as 'X Predicted Age' was then recorded on the spreadsheet under each respective case.

Examination of the Prediction Errors

While we can use the R-square values to measure the degree of 'prediction success,' it is also useful to measure the 'prediction errors'. This will allow for comparison between systems where the values for R-square had not been made available. In doing so we are examining the models for those that have the smallest prediction errors, or in other words, looking for the models that most accurately describe the sample from which they were derived.

Predicted age was compared with actual age, and mean over-estimates were calculated overall and for each year age group. Predicted ages for the cases derived by using both the Schour and Massler method and the Demirjian Canadian Population based predictive tables were also compared with actual age and mean over-estimates calculated. T-tests were undertaken to ascertain the significance, or otherwise, of the magnitude of the differences between the prediction errors of the various models. The mean overestimate results were then compared to assess the most effective model for each sex including the models for the truncated samples. As such the final regression models were chosen.

8.2.2.5 Construction of Final Predictive Models

The development and validation samples were recombined and limited at the upper end of maturity scores to a maximum of 55 as it was the 'truncated models' (M SMS-55 and F SMS-55) that were chosen as the most effective. Actual age was regressed on SMS and consecutive powers of SMS up to and including SMS^3, giving the final regression equations. These final regression equations were then used to calculate a predicted age for each case. Confidence intervals were then calculated.

Calculation of Confidence Intervals

Standard errors of estimate were then calculated for each predicted age range. This then allowed for the calculation of the confidence intervals for the models. In order to do so, the prediction errors were derived and were squared and summed to give total ‘sum of squared errors’ for each age group.

The standard error of the estimate (SEE) was then derived using the following formula:

$$SEE = \sqrt{ss / (n\text{-}k\text{-}1)}$$

Where SEE is the standard error of estimate, ss is the sum of the squared prediction errors, *n* is the sample size and *k* is the number of regressors in the model.

In order to calculate the 95% confidence intervals, the t-values for the calculated sample sizes (or more correctly the degrees of freedom) at the 0.05 level of significance were determined using the TINV function in Microsoft Excel. These values were then used to calculate the confidence intervals with the following formula:

$$CI = t \times SEE$$

Where CI is the confidence interval for a given level of significance, t is the calculated t value and SEE is the standard error of estimate.

While the above steps will provide an acceptable representation of the appropriate confidence intervals, a more conservative approach, based on the residual error from the ANOVA output is possible. A simplified confidence interval, one constant for the entire age range, has been suggested by some authors (Liversidge and Molleson, 1999). The simple confidence interval can be derived using the square root of the residual error from the ANOVA outputs to estimate the standard deviation of the predictions.

Mathematically we use:

SD= $\sqrt{\text{residual ss} / (n\text{-}k)}$ = $\sqrt{\text{residual MS}}$

where SD is the standard deviation over the entire curve, residual ss is the sum of the squared prediction errors, *n* is the sample size, *k* is the number of regressors in the model, and residual MS is the mean of the square of the residual errors (from the ANOVA output);

and CI = t x SD

where CI is the confidence interval, t is the t-critical value for the given confidence level (in this case t=1.96 for the 95% level) and SD is the standard deviation calculated above.

The results were graphed and tabled and are presented in the next chapter.

Chapter 9

Results

9.1 DESCRIPTION OF DATA

9.1.1 Assessment of Attained Stages of Development and Calculation of Chronological Age (CA)

An excerpt of the results of the overall analysis of the OPGs, including the age estimates based on the Schour and Massler charts and calculated chronological ages (CA), is contained in Appendix A2.

9.1.2 Assessment of Inter-observer Error

Rating differences between the author and another researcher are contained in Appendix A4 and are summarised in Table 9.1 below.

	Tooth							
Magnitude of disagreement	**47**	**46**	**45**	**44**	**43**	**42**	**41**	**Total**
1 Stage	10	14	12	20	17	48	29	150
2 Stages	1	0	1	0	0	3	0	5
Total	11	14	13	20	17	51	29	155

Table 9.1: Distribution of disagreements between observers, by tooth type, and by magnitude of disagreement.

For tooth 47 the assessments were not the same in 11 cases, 10 of which differed by one stage. Both examiners analysed the same 74 OPGs, which resulted in analysis of images of a total of 518 separate teeth. Both examiners agreed on the stage of development of 363 teeth, disagreeing in 155 cases. This represents an overall agreement level of 70%. Of these disagreements 150 were by one stage only, 5 by two stages and none by three or more stages.

The overall results of the assessment of inter-observer agreement are shown in Table 9.2. This table shows the distribution of agreement of assessment of tooth development stage by two examiners over all 7 mandibular teeth. Numbers in parentheses are chance-expected frequencies of agreement, e.g. 3.5=43x42/518.

	Examiner B									Total
Examiner A	**0**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	
0	38 (3.5)	4	0	0	0	0	0	0	0	42
A	5	13 (0.63)	0	0	0	0	0	0	0	18
B	0	1	16 (0.85)	3	0	0	0	0	0	20
C	0	0	6	67 (15.28)	13	1	0	0	0	87
D	0	0	0	20	81(26.88)	16	1	0	0	118
E	0	0	0	1	23	54 (15.12)	9	0	0	87
F	0	0	0	0	1	17	35 (6.60)	3	0	56
G	0	0	0	0	0	2	16	27 (3.74)	6	51
H	0	0	0	0	0	0	0	8	31 (2.79)	39
Total	43	18	22	91	118	90	61	38	37	518

Table 9.2: Distribution of tooth development stages of all 7 right mandibular teeth (47-41) as assessed by two examiners. Numbers in parentheses are chance-expected frequencies of agreement, e.g. 3.5=43x42/518.

Of the 518 teeth assessed, the observed proportion of teeth whose developmental stage was agreed upon by both examiners is:

P_o = (38+13+16+67+81+54+35+27+31)/518= 362/518 = 0.70

The chance-expected proportion of agreement is:

P_e=(3.5+0.63+0.85+15.28+26.88+15.12+6.60+3.74+2.79)/518=75.39/518=0.15

This gives an overall Kappa value:

K= (0.7-0.15)/(1- 0.15) = 0.65, a level of 'substantial reliability' according to Landis & Koch (Landis and Koch, 1977).

The inter-observer agreement of assessment of tooth development stage for each individual tooth type was analysed. Table 9.3 demonstrates this process in that it details the distribution of agreement of assessment of tooth development stage by two examiners for tooth 47.

	Examiner B									Total
Examiner A	**0**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	
0	19 (5.39)	2	0	0	0	0	0	0	0	21
A	0	1 (0.05)	0	0	0	0	0	0	0	1
B	0	1	7 (0.86)	0	0	0	0	0	0	8
C	0	0	1	8 (1.51)	4	1	0	0	0	14
D	0	0	0	0	17 (5.35)	1	0	0	0	18
E	0	0	0	0	1	9 (1.49)	0	0	0	10
F	0	0	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	1 (0.01)	0	1
H	0	0	0	0	0	0	0	0	1 (0.01)	1
Total	19	4	8	8	22	11	0	1	1	74

Table 9.3: Distribution of tooth development stage of tooth 47 as assessed by two examiners. Numbers in parentheses are chance-expected frequencies of agreement, e.g. 5.39=19x21/74.

Kappa=0.81 for tooth 47

This process was repeated for each other tooth type, the summary of these results is in Table 9.4.

Tooth	Kappa
47	0.81
46	0.76
45	0.76
44	0.68
43	0.67
42	0.18
41	0.54

Table 9.4: Kappa values, indicating levels of agreement of the stage of development between two observers for each tooth type

The inter-observer agreement for the assessment of each tooth development stage was analysed when the stages were dichotomised as 'x' and 'NOT x' over all 7 mandibular teeth examined.

Table 9.5 demonstrates this process in that it details the distribution of the dichotomised stage analysis for development stage 'A' for the combined seven teeth types.

	Examiner B		
Examiner A	**A**	**NOT A**	**Total**
A	13 (0.63)	5	18
NOT A	5	495(482.63)	500
Total	18	500	518

Table 9.5: Between examiner agreement concerning the stage of development 'A' across all 7 right mandibular teeth (47-41), dichotomised as A/NOT A (from Table 9.2). Numbers in parentheses are chance-expected frequencies of agreement, e.g. 0.63=18x18/518.

In this instance:

P_o = (13+495)/518=0.98, and

P_e =((18x18)/518+ (500x500)/518)/518=(0.63+482.63)/518=0.93

Thus Kappa = (0.98-0.93)/(1-0.93)=0.71, again indicating substantial reliability when development is assessed as being this stage.

This process was repeated for each other development stage, the summary of these results is in Table 9.6.

Stage	Kappa
0	0.87
A	0.71
B	0.75
C	0.71
D	0.60
E	0.54
F	0.55
G	0.56
H	0.79

Table 9.6: Kappa values indicating the levels of agreement between two observers for each stage of tooth development across all 7 right mandibular teeth (47-41)

Next, this process was repeated but for each individual tooth type. Table 9.7 gives an example of the results of this process in that it details the distribution of agreement of assessment concerning tooth development stage 'A' dichotomised as A/NOT A for tooth 47.

	Examiner B		
Examiner A	A	NOT A	Total
A	1	0	1
NOT A	3	70	73
Total	4	70	74

Table 9.7: Between examiner agreement concerning the stage of development 'A' for tooth 47, dichotomised as A/NOT A (from Table 9.3). Kappa=0.39

This process was repeated for each other development stage and tooth type, the summary of these results is in Table 9.8.

	Tooth						
Stage	47	46	45	44	43	42	41
0	0.93	-	0.88	0.64	-	-	-
A	0.39	-	0.8	0.69	-	-	-
B	0.86	-	0.82	0.64	-	-	-
C	0.68	0.88	0.58	0.67	0.83	0.46	0.58
D	0.8	0.83	0.68	0.66	0.45	0.19	0.48
E	0.83	0.74	0.77	0.67	0.53	0.09	0.28
F	-	0.62	0.71	0.72	0.76	0.1	0.37
G	1	0.75	-	-	-	0.04	0.63
H	1	0.8	1	1	1	0.5	0.86

Table 9.8: Kappa values indicating the levels of agreement between two observers for each stage of tooth development by individual tooth type

9.1.3 Assessment of Intra-Observer Error

The results of the comparison between the initial and later re-analysed sets of assessments, undertaken by the author are contained in Appendix A5 and are summarized in Table 9.9 below.

Magnitude of disagreement	Tooth							
	47	46	45	44	43	42	41	Total
1 Stage	24	27	30	28	40	29	31	209
2 Stages	0	1	0	0	0	1	1	3
Total	24	28	30	28	40	30	32	212

Table 9.9: Distribution of disagreements between repeated observations by the same observer, by tooth type, and by magnitude of disagreement

For tooth 47 the assessments were not the same in 24 cases, all of which differed by one stage only. In this part, 181 OPGs were examined which resulted in the analysis of images of a total of 1267 separate teeth. Of this number the assessment by the author was consistent on the classification of stage of development of 1055 teeth, disagreeing on stage of development of 212 teeth. This represents an overall level of agreement of 83%, which was consistent with the agreement scores obtained when doing pre-calibration assessments on the training package. Of these disagreements 209 were out by one stage only, 3 by two stages and none by three or more stages.

The overall results of the assessment of intra-observer agreement are shown in Table 9.10. This table shows the distribution of agreement of assessment (over all 7 mandibular teeth) of tooth development stage. Numbers in parentheses are chance-expected frequencies of agreement, e.g. 0.57=26x28/1267.

	ANALYSIS I									Total
ANALYSIS II	**0**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	
0	(0.57) 23	3	0	0	0	0	0	0	0	26
A	4	(0.53) 21	0	0	0	0	0	0	0	25
B	1	3	(2.18) 44	12	0	0	0	0	0	60
C	0	0	2	(8.11) 83	10	1	0	0	0	96
D	0	0	0	12	(14.79) 113	6	0	0	0	131
E	0	0	0	0	20	(15.59) 95	2	2	0	119
F	0	0	0	0	0	64	(42.72) 183	12	0	259
G	0	0	0	0	0	0	24	(24.35) 139	24	187
H	0	0	0	0	0	0	0	12	(108.02) 352	364
Total	28	27	46	107	143	166	209	165	376	1267

Table 9.10: Distribution of tooth development stages of all 7 right mandibular teeth (47-41) as assessed in duplicate observations by the same observer. Numbers in parentheses are chance-expected frequencies of agreement, e.g. 0.57=26x28/1267.

Of the 1267 teeth assessed, the observed proportion of teeth whose developmental stage was agreed upon on both occasions is:

P_o = (23+21+44+83+113+95+183+139+352)/1267= 1053/517 = 0.83

The chance-expected proportion of agreement is:

P_e=(0.57+0.53+2.18+8.11+14.79+15.59+42.72+24.35+108.02)/1267

=216.86/1267=0.17

This gives an overall Kappa value:

K= (0.83-0.17)/(1- 0.17) = 0.80, a level of 'substantial reliability' according to Landis & Koch (Landis and Koch, 1977).

The intra-observer agreement of assessment of tooth development stage for each individual tooth type was analysed. Table 9.11 demonstrates this process in that it details the distribution of agreement of the assessments of tooth development stage for tooth 47 on both occasions.

	ANALYSIS I									Total
ANALYSIS II	0	A	B	C	D	E	F	G	H	
0	(1.41) 14	2	0	0	0	0	0	0	0	16
A	2	(0.5) 7	0	0	0	0	0	0	0	9
B	0	1	(1.68) 16	2	0	0	0	0	0	19
C	0	0	0	(1.57) 15	0	0	0	0	0	15
D	0	0	0	2	(2.21) 18	0	0	0	0	20
E	0	0	0	0	2	(2.49) 16	0	0	0	18
F	0	0	0	0	0	9	(9.09) 35	3	0	47
G	0	0	0	0	0	0	0	(3.71) 24	0	24
H	0	0	0	0	0	0	0	1	(0.86) 12	13
Total	16	10	16	19	20	25	35	28	12	181

Table 9.11: Distribution of tooth development stage of tooth 47 as assessed in duplicate observations by the same observer. Numbers in parentheses are chance-expected frequencies of agreement, e.g. 1.41=16x16/181

Kappa=0.85 for tooth 47

This process was repeated for each other tooth type, the summary of these results is in Table 9.12.

Tooth	Kappa
47	0.85
46	0.79
45	0.80
44	0.81
43	0.72
42	0.77
41	0.71

Table 9.12: Kappa values, indicating levels of agreement of the stage of development in duplicate observations, by the same observer for each tooth type

The intra-observer agreement for the assessment of each tooth development stage was analysed when the stages were dichotomised as 'x' and 'NOT x' over all 7 mandibular teeth examined.

Table 9.13 demonstrates this process in that it details the distribution of the dichotomised stage analysis for development stage 'A' for the combined seven teeth types.

	ANALYSIS I		
ANALYSIS II	**A**	**NOT A**	**Total**
A	21(0.53)	4	25
NOT A	6	1236 (1215.53)	1242
Total	27	1240	1267

Table 9.13: Intra-examiner agreement concerning the stage of development 'A' across all 7 right mandibular teeth (47-41), dichotomised as A/NOT A (from Table 9.10). Numbers in parentheses are chance-expected frequencies of agreement, e.g. 0.53=27x25/1267.

In this instance:

Kappa = 0.80, again indicating substantial reliability when development is assessed as being this stage.

This process was repeated for each other development stage, the summary of these results is in Table 9.14 below.

Stage	Kappa
0	0.85
A	0.80
B	0.82
C	0.80
D	0.80
E	0.63
F	0.73
G	0.76
H	0.93

Table 9.14: Kappa values indicating the levels of agreement in duplicate observations by the same observer, for each stage of tooth development across all 7 right mandibular teeth (47-41)

Next, this process was repeated but for each individual tooth type. Table 9.15 gives an example of the results of this process in that it details the distribution of agreement of assessment concerning tooth development stage 'A' dichotomised as A/NOT A for tooth 47.

	ANALYSIS I		
ANALYSIS II	**A**	**NOT A**	**Total**
A	7	2	9
NOT A	3	169	172
Total	10	171	181

Table 9.15: Intra-examiner agreement concerning the stage of development 'A' for tooth 47, dichotomised as A/NOT A (from Table 9.11). Kappa=0.72

This process was repeated for each other development stage and tooth type, the summary of these results is in Table 9.16.

	Tooth						
Stage	**47**	**46**	**45**	**44**	**43**	**42**	**41**
0	0.86	-	0.81	-	-	-	-
A	0.72	-	0.83	-	-	-	-
B	0.91	-	0.74	0.79	-	-	-
C	0.87	0.66	0.72	0.76	0.86	0.86	0.65
D	0.89	0.95	0.72	0.83	0.55	0.55	0.82
E	0.71	0.63	0.77	0.7	0.57	0.57	0.57
F	0.81	0.57	0.84	0.78	0.64	0.64	0.69
G	0.91	0.78	0.75	0.82	0.65	0.65	0.64
H	0.96	0.86	0.89	0.96	0.95	0.95	0.9

Table 9.16: Kappa values indicating the levels of agreement in duplicate observations by the same observer, for each stage of tooth development by individual tooth type

9.1.4 Demirjian Maturity Score (DMS)

Both tooth-specific mean self-weighted scores and case mean DMS values by age are given in Tables 9.17 and 9.18.

AGE			MALES - MEAN DEMIRJIAN SELF-WEIGHTED SCORES							DMS
	n	%	47	46	45	44	43	42	41	TOTAL
1	2	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	51	3.1	0.04	1.97	0.04	0.36	0.00	0.11	0.93	3.39
3	110	6.7	0.92	5.37	0.91	3.39	0.15	1.27	4.17	15.47
4	111	6.8	2.99	6.69	2.68	5.96	0.76	2.89	5.36	26.62
5	120	7.3	4.98	7.88	4.69	7.77	3.12	4.70	6.43	39.53
6	82	5.0	6.77	10.19	6.51	9.87	5.29	6.08	8.07	52.77
7	120	7.3	8.59	12.83	8.66	12.38	7.68	7.84	10.22	68.19
8	120	7.3	9.03	13.81	9.44	13.14	8.16	9.05	11.87	74.43
9	142	8.7	11.01	14.74	11.19	14.40	9.41	11.18	14.34	86.28
10	143	8.7	11.77	15.33	11.62	14.79	10.10	11.86	14.77	90.25
11	112	6.8	12.16	16.05	12.00	15.14	10.53	12.57	15.07	93.52
12	82	5.0	12.58	16.66	12.33	15.49	11.22	13.10	15.05	96.43
13	67	4.1	12.72	16.80	12.53	15.71	11.51	13.20	15.10	97.56
14	74	4.5	12.97	16.80	12.87	15.99	11.91	13.20	15.10	98.84
15	71	4.3	13.21	16.80	13.03	16.05	11.97	13.20	15.10	99.35
16	62	3.8	13.39	16.80	13.12	16.07	11.97	13.20	15.10	99.65
17	40	2.4	13.60	16.80	13.20	16.10	12.00	13.20	15.10	100.00
18	54	3.3	13.60	16.80	13.20	16.10	12.00	13.20	15.10	100.00
19	32	2.0	13.60	16.80	13.20	16.10	12.00	13.20	15.10	100.00
20	29	1.8	13.60	16.80	13.20	16.10	12.00	13.20	15.10	100.00
21	12	0.7	13.60	16.80	13.20	16.10	12.00	13.20	15.10	100.00
23	1	0.1	13.60	16.80	13.20	16.10	12.00	13.20	15.10	100.00
Total	1637	100								

Table 9.17: Male mean Demirjian Maturity Score (column Total) derived from tooth-specific mean self-weighted scores, by chronological age.

AGE			FEMALE - MEAN DEMIRJIAN SELF-WEIGHTED SCORES							DMS
	n	%	47	46	45	44	43	42	41	TOTAL
1	3	0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	27	1.7	0.00	2.07	0.00	0.60	0.00	0.73	2.44	5.78
3	91	5.6	0.83	3.61	0.85	3.03	0.32	1.69	4.21	13.89
4	97	6.0	2.80	4.97	2.75	5.20	1.71	3.02	5.40	25.13
5	116	7.1	5.08	6.43	4.99	7.72	4.13	4.93	6.86	40.01
6	85	5.2	7.30	9.34	7.14	10.28	6.06	6.71	8.97	55.72
7	109	6.7	8.60	11.28	9.25	11.84	7.51	8.40	11.04	67.93
8	98	6.0	9.74	12.54	10.45	12.98	8.67	10.44	13.67	78.49
9	98	6.0	11.18	13.65	11.46	13.83	10.00	12.07	15.22	87.42
10	120	7.4	12.14	14.24	12.04	14.32	10.60	12.84	15.55	91.72
11	90	5.5	12.72	14.88	12.40	14.73	11.44	13.56	15.67	95.42
12	103	6.3	13.04	15.29	12.74	15.08	12.13	13.80	15.80	97.89
13	89	5.5	13.18	15.37	12.86	15.28	12.33	13.77	15.80	98.58
14	83	5.1	13.37	15.40	13.13	15.45	12.47	13.80	15.80	99.42
15	83	5.1	13.60	15.40	13.23	15.49	12.48	13.80	15.80	99.79
16	83	5.1	13.70	15.40	13.26	15.49	12.50	13.80	15.80	99.96
17	78	4.8	13.75	15.40	13.30	15.50	12.50	13.80	15.80	100.05
18	54	3.3	13.78	15.40	13.29	15.50	12.50	13.80	15.80	100.07
19	58	3.6	13.80	15.40	13.30	15.50	12.50	13.80	15.80	100.10
20	40	2.5	13.80	15.40	13.30	15.50	12.50	13.80	15.80	100.10
21	14	0.9	13.80	15.40	13.30	15.50	12.50	13.80	15.80	100.10
22	3	0.2	13.80	15.40	13.30	15.50	12.50	13.80	15.80	100.10
23	1	0.1	13.80	15.40	13.30	15.50	12.50	13.80	15.80	100.10
TOTAL	1623	100								

Table 9.18: Female mean Demirjian Maturity Score (column Total) derived from tooth-specific mean self-weighted scores, by chronological age.

For example, in relation to females for the 3 year-old age group (of which there are 91), the mean tooth score for tooth 47 is 0.83, and the overall mean DMS is 13.89.

9.1.5 Simple Maturity Score (SMS)

Both tooth-specific mean numerical maturity scores and case mean SMS values are given in Tables 9.19 and 9.20.

AGE			MALE - MEAN SIMPLE NUMERICAL SCORES							SMS
	n	%	47	46	45	44	43	42	41	TOTAL
1	2	0.1	0.00	3.00	0.00	1.00	3.00	3.00	3.00	13.00
2	51	3.1	1.06	3.37	0.02	1.09	3.00	3.04	3.22	14.67
3	110	6.7	0.32	4.05	0.39	1.90	3.04	3.45	4.00	17.14
4	111	6.8	1.65	4.63	1.58	2.84	3.19	4.05	4.53	22.41
5	120	7.3	2.78	5.13	2.75	3.48	3.78	4.73	5.08	27.72
6	82	5.0	3.43	5.91	3.45	4.11	4.35	5.30	5.84	32.40
7	120	7.3	4.02	6.70	4.28	4.82	5.01	6.03	6.65	37.49
8	120	7.3	4.17	6.99	4.55	5.09	5.20	6.48	7.14	39.58
9	142	8.7	5.00	7.29	5.41	5.73	5.71	7.25	7.80	44.19
10	143	8.7	5.46	7.50	5.76	6.01	6.06	7.50	7.92	46.20
11	112	6.8	5.90	7.74	6.14	6.44	6.38	7.77	7.99	48.36
12	82	5.0	6.48	7.95	6.63	6.98	6.96	7.96	7.99	50.95
13	67	4.1	6.78	8.00	6.97	7.34	7.28	8.00	8.00	52.37
14	74	4.5	7.19	8.00	7.51	7.81	7.85	8.00	8.00	54.36
15	71	4.3	7.49	8.00	7.75	7.92	7.94	8.00	8.00	55.10
16	62	3.8	7.73	8.00	7.89	7.95	7.95	8.00	8.00	55.52
17	40	2.4	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
18	54	3.3	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
19	32	2.0	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
20	29	1.8	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
21	12	0.7	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
23	1	0.1	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
TOTAL	1637	100								

Table 9.19: Male mean Simple Maturity Score (column Total) derived from tooth-specific mean numerical maturity scores, by chronological age.

AGE			FEMALE - MEAN SIMPLE NUMERICAL SCORES							SMS
	n	%	47	46	45	44	43	42	41	TOTAL
1	3	0.2	0.00	3.00	0.00	1.00	3.00	3.00	3.00	13.00
2	27	1.7	0.00	3.59	0.00	1.19	3.00	3.26	3.56	14.56
3	91	5.6	0.38	4.07	0.34	2.07	3.09	3.60	4.00	17.47
4	97	6.0	1.51	4.69	1.52	2.90	3.46	4.10	4.54	22.67
5	116	7.1	2.72	5.28	2.73	3.69	4.12	4.84	5.25	28.62
6	85	5.2	3.51	6.20	3.53	4.39	4.66	5.49	6.06	33.84
7	109	6.7	3.91	6.70	4.28	4.83	5.10	6.08	6.71	37.61
8	98	6.0	4.28	7.03	4.81	5.23	5.52	6.77	7.44	41.07
9	98	6.0	4.97	7.40	5.41	5.74	6.06	7.35	7.85	44.78
10	120	7.4	5.54	7.60	5.84	6.14	6.38	7.63	7.93	47.07
11	90	5.5	6.13	7.82	6.34	6.76	6.97	7.91	7.97	49.90
12	103	6.3	6.67	7.96	6.89	7.30	7.52	8.00	8.00	52.35
13	89	5.5	6.93	7.99	7.15	7.63	7.81	7.99	8.00	53.49
14	83	5.1	7.28	8.00	7.65	7.92	7.96	8.00	8.00	54.81
15	83	5.1	7.66	8.00	7.86	7.98	7.98	8.00	8.00	55.47
16	83	5.1	7.83	8.00	7.93	7.99	8.00	8.00	8.00	55.75
17	78	4.8	7.92	8.00	8.00	8.00	8.00	8.00	8.00	55.92
18	54	3.3	7.96	8.00	7.98	8.00	8.00	8.00	8.00	55.94
19	58	3.6	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
20	40	2.5	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
21	14	0.9	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
22	3	0.2	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
23	1	0.1	8.00	8.00	8.00	8.00	8.00	8.00	8.00	56.00
TOTAL	1623	100								

Table 9.20: Female mean Simple Maturity Score (column Total) derived from tooth-specific mean numerical maturity scores, by chronological age.

For example, in relation to females for the 3 year-old age group (of which there are 91), the mean tooth score for tooth 47 is 0.38, and the overall mean SMS is 17.47.

9.1.6 Simple maturity score by age and sex

The mean ages for a given SMS were calculated for each sex. They are represented in Figure 9.1 below.

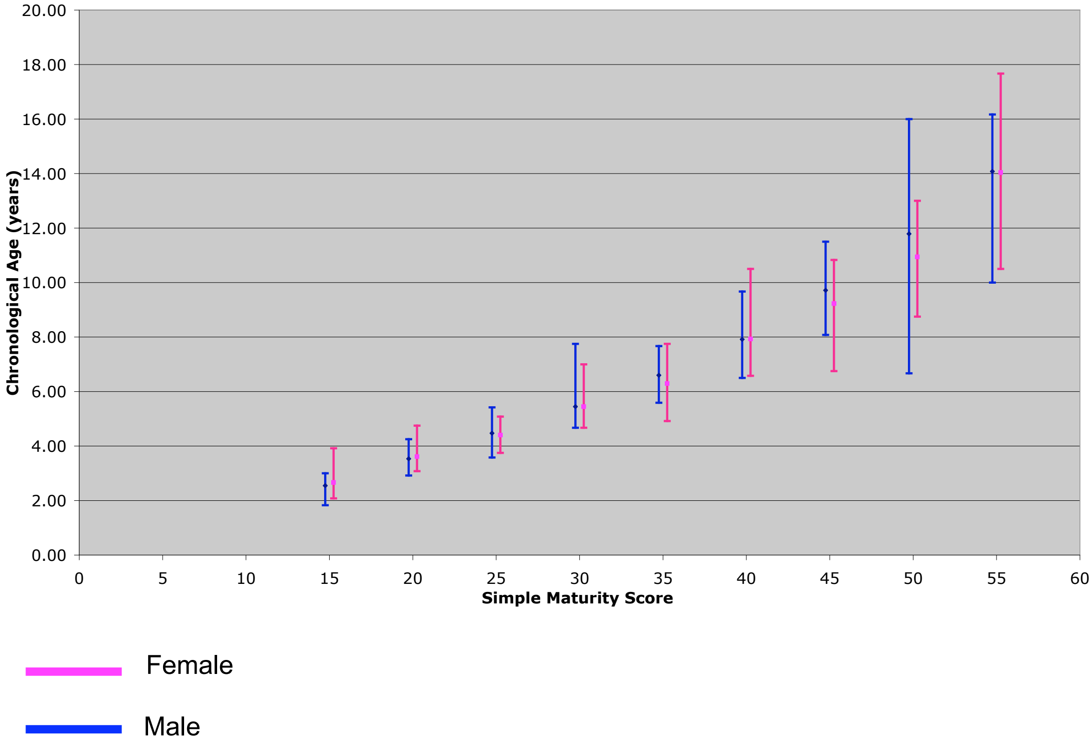

Figure 9.1: Mean age by SMS (centred dots) for the entire sample. The blue and pink lines represent the range for a given SMS for males and females respectively.

The age ranges depicted by the blue and pink lines in the above figures show the large natural variation in tooth development that can be observed for any given age, with both males and females showing similar variation across the entire sample. The tendency towards a larger variation as age increases has been noted by many authors and is discussed further in the next chapter. It should be noted that this chart is based upon those cases where scores equalled an SMS of 15, 20, 25 etc exactly, this resulted in small sample sizes. As such this chart should be used to give an indication only of the trends of increasing variation with age. These ranges are also consistent with that represented by the height of the ‘data cloud’ represented in Figures 9.6 and 9.7. These ranges will be similar but not identical to Figures 9.6 and 9.7 as these charts were based upon data from the validation sample only, whereas this current chart (Fig 9.1) is based on the entire data set. Age and sex differences in SMS were evaluated by t-tests and are summarised in Table 9.21 below.

Sex differences in mean chronological age by SMS				
SMS	Mean Difference (years)	t	t-critical at p<0.05	p
15	0.12	1.21	2.02	0.24
20	0.08	0.43	2.06	0.67
25	-0.14	0.98	2.02	0.33
30	-0.01	0.02	2.03	0.99
35	-0.30	1.55	2.02	0.13
40	-0.01	0.06	2.01	0.95
45	-0.49	2.64	1.99	0.01
50	-0.84	2.89	1.99	0.01
55	-0.05	0.21	1.97	0.83

Table 9.21: Mean differences between male and female chronological age, t-scores and associated p-values by SMS. The t-critical values are given for the associated sample sizes with p<0.05.

By way of explanation, to compare females and males with an SMS of 15, although the mean age for females is 0.12 years greater than that for males of the same SMS (and hence the same level of dental maturity), the t-test result of 1.21 indicates that these differences in chronological age for a given level of dental maturity are not significant. In Table 9.21 it can be seen that SMS of 45 and 50 were associated with significant age differences between sexes. As this significant sexual dimorphism exists, even if for only part of the entire age range, it is important that separate prediction curves be used for each sex.

9.2 DATA ANALYSIS

9.2.1 Age Estimates According to the Demirjian System

The applicability of the published Demirjian standards for use on an Australian sample was assessed by examining the prediction errors obtained when these standards were used on the development sample. These results are summarised in Table 9.22 below.

CA (years)	Male n	MEAN OVERESTIMATE OF CANADIAN PREDICTED AGE (CPA) - MALE (years)	95% CONFIDENCE INTERVAL (years)	Femle n	MEAN OVERESTIMATE OF CANADIAN PREDICTED AGE (CPA) - FEMALE (years)	95% CONFIDENCE INTERVAL (years)
1	0	-	-	1	-	-
2	19	0.68	0.56-0.70	11	0.46	0.28-0.64
3	41	0.26	0.10-0.42	32	0.04	-0.13-0.21
4	34	0.42	0.17-0.67	29	0.25	-0.08-0.58
5	46	0.72	0.5-0.94	43	0.69	0.48-1.00
6	19	0.91	0.6-1.22	23	0.59	0.21-0.97
7	52	0.97	0.69-1.25	39	0.53	0.31-0.75
8	41	0.62	0.29-0.95	29	0.31	0.08-0.54
9	45	0.82	0.54-1.10	31	0.50	0.1-0.9
10	42	0.73	0.40-1.06	41	0.53	0.2-0.86
11	38	0.77	0.40-1.14	31	0.66	0.09-1.23
12	23	0.65	0.33-0.97	27	0.97	0.62-1.32
13	21	0.70	0.27-1.13	24	0.69	0.29-1.09
14	20	0.02	-0.3-0.34	20	0.34	0.05-0.63
15	8	-0.80	-1.28--0.32	12	-0.57	-0.96--0.16
16	6	-1.24	-2.03--0.45	4	-2.18	-3.42--0.94
OVERALL	455	0.61	0.52-0.7	401	0.42	0.32-0.52
t test		13.99			8.59	
p		<0.000			<0.000	

Table 9.22: Mean overestimates of predicted age by Chronological Age (CA) and sex, where predicted age is calculated using the Demirjian Maturity Score.

By way of explanation, the mean age overestimation for male cases in the 2 year-old age group (of which there are 19 in the development sample) is 0.68 years. It can be seen from these results above in Table 9.22, that up to the age of 14 years the use of the Canadian standards developed by Demirjian consistently tend to overestimate age. The magnitude of this overestimate varies from 0.02 –0.97 years but significantly underestimates ages once the child reaches 15 years. The overall mean overestimates are 0.61 years for males and 0.42 years for females, and were both highly significant ($p<0.000$).

9.2.2 Age Estimates According to Alternative Models

a) REGRESSION ANALYSIS

The final male and female models were all based upon the SMS and used 5 predictors. Models based on the SMS scoring system that were truncated at a score of 55 were also chosen for further examination and were based upon 3 predictors. Appendix A3 contains a series of charts depicting the various regression curves superimposed on a plot of the data from which they were derived. These charts depict the full data set and the progression of models, as the number of regressors increases, up to the selected 'M SMS' model. This succession of curves demonstrates that as the number of predictors increases so does the visually assessed accuracy of fit of the curve.

The regression results for the selected models are given in Tables 9.25-9.28 and Figures 9.2-9.5.

Male:

SUMMARY OUTPUT

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	12338.84687	2467.769374	1577.382414	0
Residual	543	849.5078673	1.564471211		
Total	548	13188.35474			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-35.1255011	8.65465625	-4.05856686	5.66292E-05
SMS	6.785337241	1.519073148	4.46676136	9.6668E-06
SMS^2	-0.47004105	0.100104414	-4.69550776	3.37235E-06
SMS^3	0.015837564	0.003117943	5.079491626	5.21157E-07
SMS^4	-0.00025379	4.62315E-05	-5.48959877	6.19226E-08
SMS^5	1.56316E-06	2.62726E-07	5.949772469	4.8162E-09

Regression Statistics	
Multiple R	0.967257213
R Square	0.935586517
Adjusted R Square	0.934993391
Standard Error	1.250788236
Observations	549

Table 9.25: Regression calculation output for Male development sample where Chronological Age was regressed on Simple Maturity Score to increasing powers. In this final selected case the predictors were SMS, SMS^2, SMS^3, SMS^4, and SMS^5.

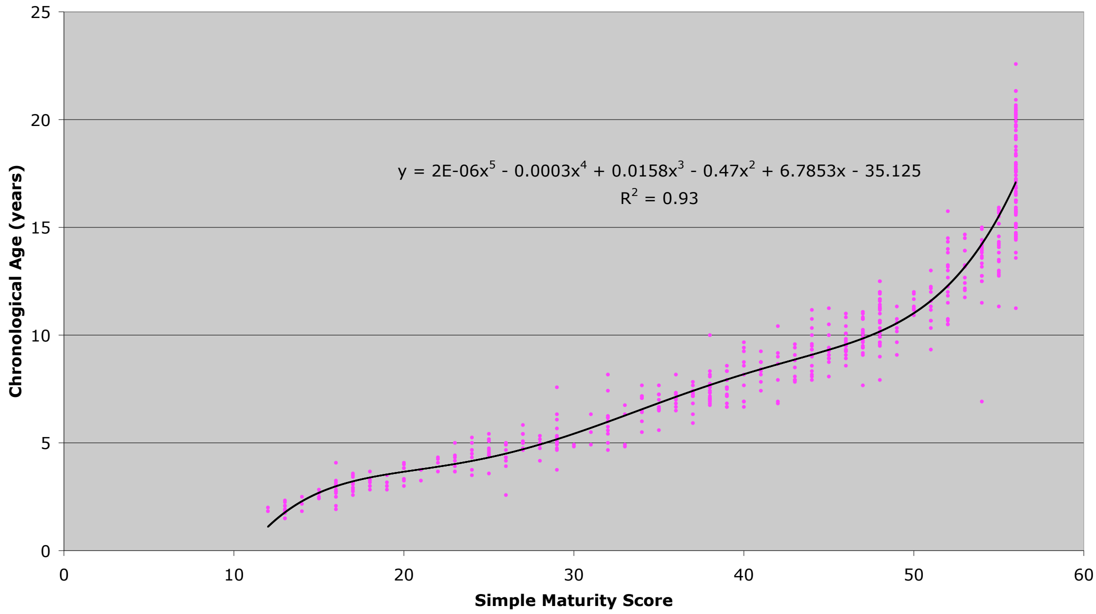

Figure 9.2: Chronological Age against Simple Maturity Score for the Male development sample. Superimposed is the regression curve described in the summary output Table 9.25 above.

With reference to Table 9.25, the addition of the final predictor, SMS^5, leaves the other four predictors with significant coefficients.

From the ANOVA table one can see the F value of 1577.38 is well above the critical value of F thus giving an associated p=0. The given equation is accepted as valid, with all regression parameters jointly statistically significant. This provides, in effect, a double check on the validity of the model.

The final regression formula is:

$$M (SMS) PA = -35.12550108+6.785337241*x-0.470041052*x^2+0.015837564*x^3-0.000253792*x^4+1.56316E-06*x^5$$

Where M (SMS) PA, is males' predicted age and x is simple maturity score (SMS) derived for a given case. The upper limit of age prediction for this model is 17.1 years.

Female:

SUMMARY OUTPUT

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	13185.75428	2637.150856	1404.405904	2.1859E-303
Residual	531	997.0957118	1.877769702		
Total	536	14182.84999			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-56.6711957	11.71863673	-4.83598878	1.73792E-06
SMS	10.50568252	1.992396006	5.272888766	1.95762E-07
SMS^2	-0.71007363	0.127948574	-5.54967992	4.52384E-08
SMS^3	0.023113854	0.003901042	5.925045627	5.6182E-09
SMS^4	-0.00035873	5.68147E-05	-6.31408079	5.74569E-10
SMS^5	2.1442E-06	3.17995E-07	6.742877213	4.06242E-11

Regression Statistics	
Multiple R	0.964208009
R Square	0.929697084
Adjusted R Square	0.929035098
Standard Error	1.370317373
Observations	537

Table 9.26: Regression calculation output for Female development sample where Chronological Age was regressed on Simple Maturity Score to increasing powers. In this final selected case the predictors were SMS, SMS^2, SMS^3, SMS^4, and SMS^5.

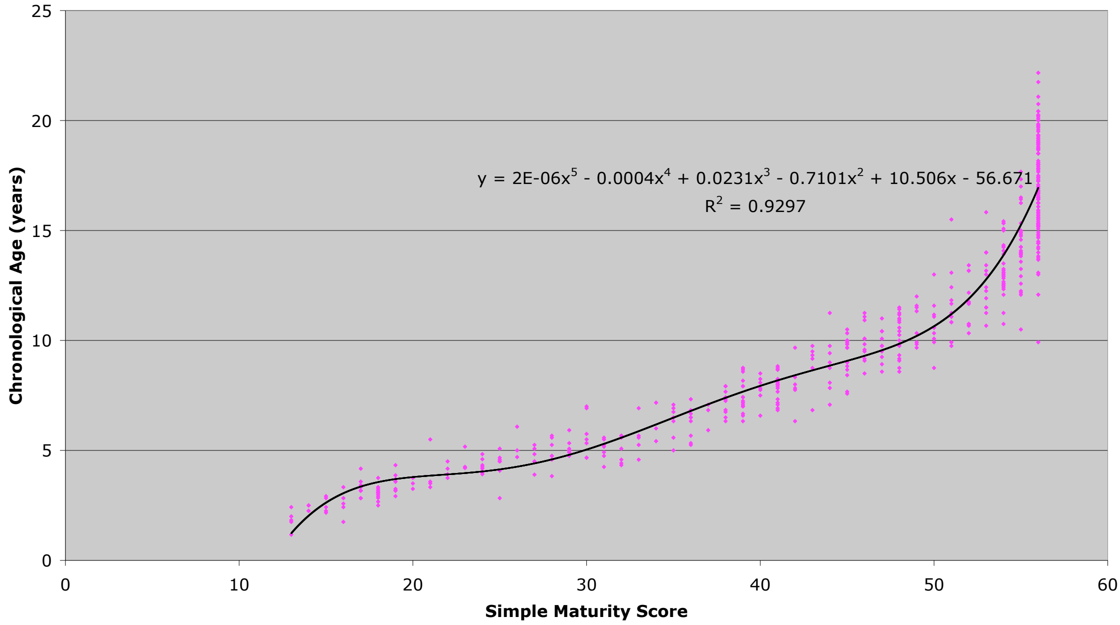

Figure 9.3: Chronological Age against Simple Maturity Score for the Female development sample. Superimposed is the regression curve described in the summary output Table 9.26 above.

With reference to Table 9.26, the addition of the final predictor, SMS^5, leaves the other four predictors with significant coefficients.

From the ANOVA table one can see the F value of 1404.41 is well above the critical value of F thus giving p=2.19E-303 which is far less than the threshold value p=0.05. The given equation is accepted as valid, with all regression parameters jointly statistically significant. This again provides, in effect, a double check on the validity of the model.

The final regression formula is:

F (SMS) PA =-56.67119572+10.50568252*x-

$0.710073632*x^2+0.023113854*x^3-0.000358732*x^4+2.1442E-06*x^5$

Where F (SMS) PA, is the females' predicted age and x is simple maturity score (SMS) derived for a given case. The upper limit of age prediction for this model is 17 years.

Male SMS truncated to 55:

SUMMARY OUTPUT

ANOVA

	df	SS	MS	F	Significance F
Regression	3	5373.945263	1791.315088	2303.552561	5.369E-273
Residual	451	350.7118172	0.777631524		
Total	454	5724.65708			

	Coefficients	Standard Error	t Stat	P-value
Intercept	-2.95563111	0.895304688	-3.30125726	0.00103897
SMS	0.510327182	0.090353546	5.648114586	2.87587E-08
SMS^2	-0.01213662	0.002769011	-4.38301606	1.45765E-05
SMS^3	0.000153736	2.64196E-05	5.818995459	1.12409E-08

Regression Statistics	
Multiple R	0.968884216
R Square	0.938736624
Adjusted R Square	0.938329107
Standard Error	0.881834181
Observations	455

Table 9.27: Regression calculation output for Male truncated development sample where Chronological Age was regressed on Simple Maturity Score to increasing powers. In this final selected case the predictors were SMS, SMS^2, and SMS^3

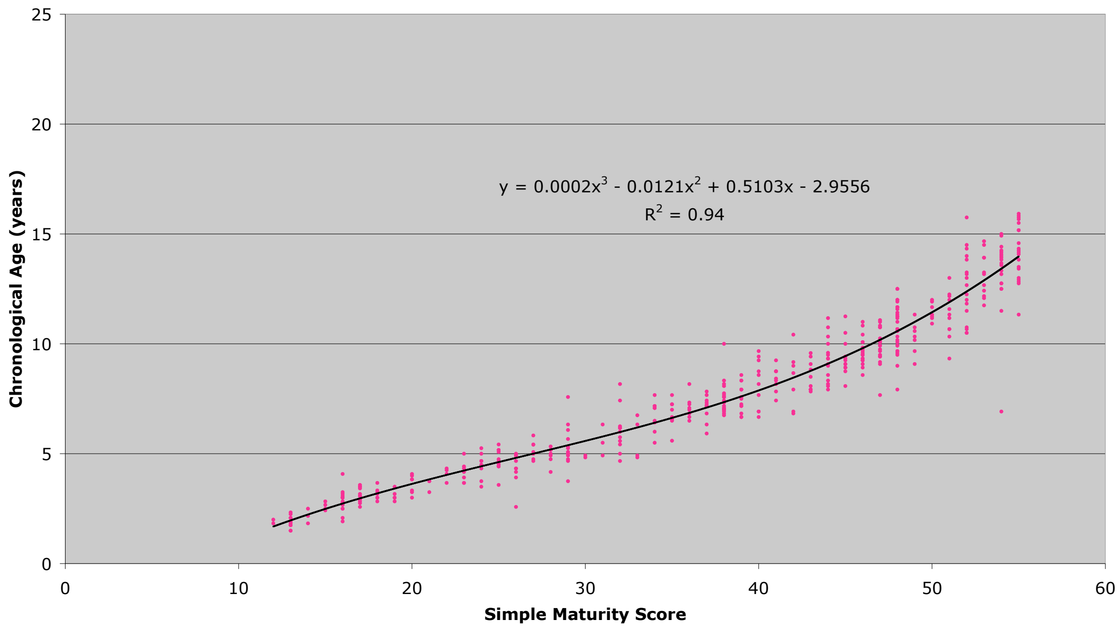

Figure 9.4: Chronological Age against Simple Maturity Score for the Male truncated development sample. Superimposed is the regression curve described in the summary output Table 9.27 above.

With reference to Table 9.27, the addition of the final predictor, SMS^3, leaves the other two predictors with significant coefficients.

From the ANOVA table one can see the F value of 2303.6 is well above the critical value of F thus giving p=5.3E-273 which is far less than the threshold value p=0.05. The given equation is accepted as valid, with all regression parameters jointly statistically significant. This again provides, in effect, a double check on the validity of the model.

The final regression formula is:

M (SMS-55) PA $=-2.955631107+0.510327182*x-0.012136619*x^2+0.000153736*x^3$

Where M (SMS-55) PA, is the male predicted age based on the SMS system whereby any case with a SMS above 55 is excluded and x is simple maturity score (SMS) derived for a given case. The upper limit of age prediction for this model is 14 years.

Female SMS truncated to 55:

SUMMARY OUTPUT

ANOVA

	df	SS	MS	F	Significance F
Regression	3	5251.945316	1750.648439	1937.997288	1.2745E-236
Residual	397	358.6214668	0.903328632		
Total	400	5610.566783			

	Coefficients	Standard Error	t Stat	P-value
Intercept	-3.10192581	1.183148933	-2.62175431	0.009084165
SMS	0.55143409	0.115689084	4.7665179	2.63477E-06
SMS^2	-0.01452478	0.003451609	-4.20811996	3.18688E-05
SMS^3	0.000184658	3.21137E-05	5.750129603	1.78135E-08

Regression Statistics	
Multiple R	0.967512823
R Square	0.936081063
Adjusted R Square	0.935598048
Standard Error	0.950436022
Observations	401

Table 9.28: Regression calculation output for Female truncated development sample where Chronological Age was regressed on Simple Maturity Score to increasing powers. In this final selected case the predictors were SMS, SMS^2, and SMS^3.

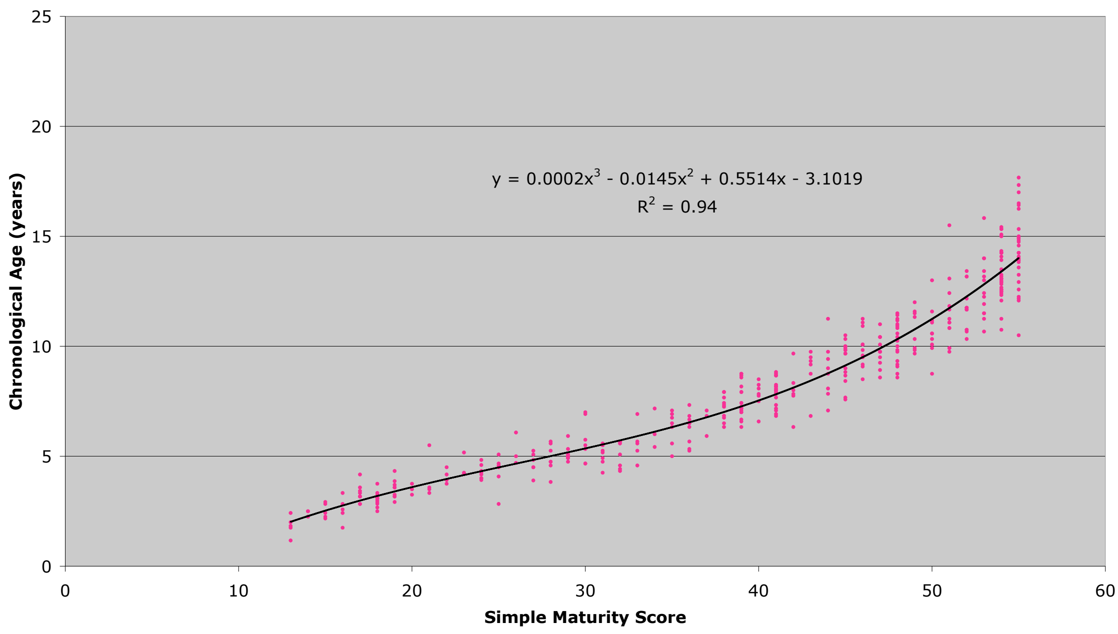

Figure 9.5: Chronological Age against Simple Maturity Score for the Female truncated development sample. Superimposed is the regression curve described in the summary output Table 9.28 above.

With reference to Table 9.28, the addition of the final predictor, SMS^3, leaves the other two predictors with significant coefficients.

From the ANOVA table one can see the F value of 1938 is well above the critical value of F thus giving p=1.27E-236 which is far less than the threshold value p=0.05. The given equation is accepted as valid, with all regression parameters jointly statistically significant. This again provides, in effect, a double check on the validity of the model.

The final regression formula is:

F (SMS-55) PA=-3.101925811+0.55143409x-0.014524784*x^2+0.000184658*x^3

Where F (SMS-55) PA, is the female predicted age based on the SMS system whereby any case with a SMS above 55 is excluded and x is simple maturity score (SMS) derived for a given case. The upper limit of age prediction for this model is 14 years.

For use in later analysis the preferred models for a truncated age range using the DMS were also selected, again based upon the highest statistically significant R-square values. The values used in the models were obtained from the relevant regression outputs as illustrated above. The final formulae for the DMS truncated models are:

M (DMS-992) PA=1.727123208+0.187848007*x-

0.010357839*x^2+0.00034212*x^3-4.55617E-06*x^4+2.10606E-08*x^5

Where M (DMS-992) PA is the male predicted age based on the DMS system whereby any case with a score above 99.2 is excluded and x is Demirjian maturity score (DMS) derived for a given case. The upper limit of age prediction for this model is 13.5 years.

$$F\ (DMS\text{-}995)\ PA=1.371510916+0.279266233*x-0.014893691*x^2+0.000424963*x^3-5.20249E\text{-}06*x^4+2.28689E\text{-}08*x^5$$

Where F (DMS-995) PA is the female predicted age based on the DMS system whereby any case with a score above 99.5 is excluded and x is Demirjian maturity score (DMS) derived for a given case. The upper limit of age prediction for this model is also 13.5 years.

At this stage the separate Male and Female models for both the SMS based system and the truncated SMS version (SMS-55) were compared against each other. While the Male and Female SMS models had a larger age range than the Male and Female SMS-55 models, the curves of the latter visually appear to better fit the scatter plot also having slightly higher values for R-square (0.94 compared to 0.93). By way of illustrating these points the scatter plots and regression curves for SMS and SMS-55 for each sex have been superimposed and are reproduced in Figures 9.6 and 9.7 below.

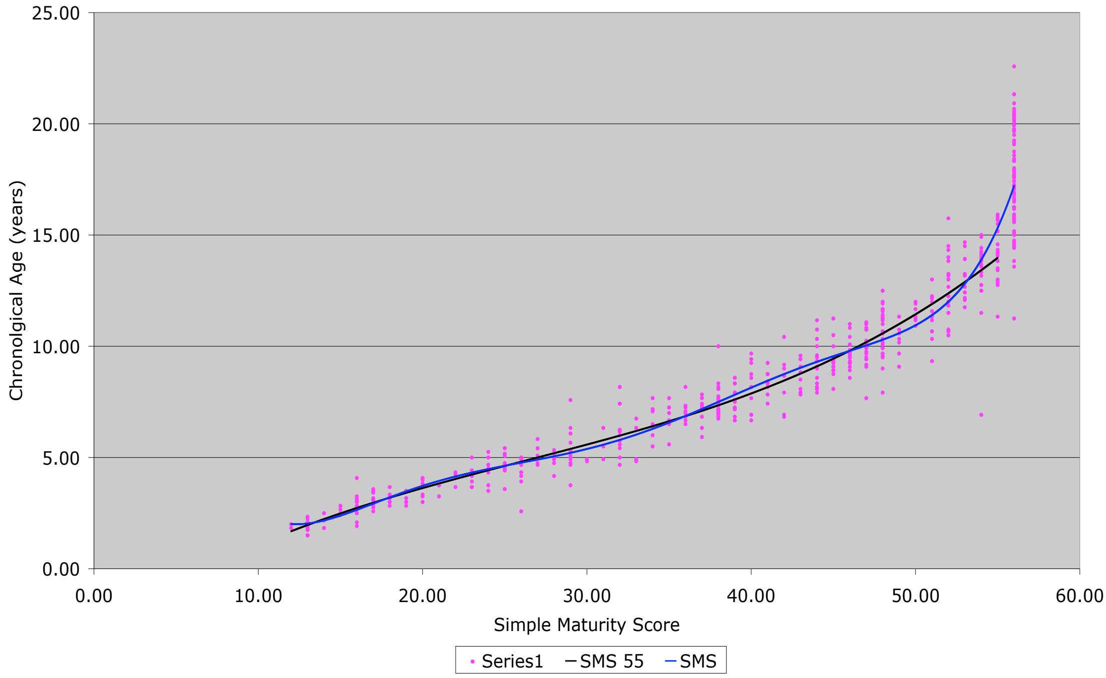

Figure 9.6: Chronological Age against Simple Maturity Score for the male development sample. Superimposed are the regression curves for the full SMS data set (heavy blue line) and that of the SMS-55 truncated data set (thin black line).

Figure 9.7: Chronological Age against Simple Maturity Score for the female development sample. Superimposed are the regression curves for the full SMS data set (heavy blue line) and that of the SMS-55 truncated data set (thin black line).

In the younger age groups the curves appear similar but while the SMS models have a greater age range than those of SMS-55, it appears that these high-end scores distort the curve upwards in the higher scores resulting in potentially larger prediction errors in these older age groups. It is with this point in mind that the prediction errors are examined in the following sections.

b) TEST OF PREDICTIVE MODELS

Predicted Age (PA) Using Selected Regression Models

Having derived the above equations from the development sample they were then applied to the validation sample to obtain predicted age.

Examination of the Prediction Errors

Predicted age overestimates for each model were compared. These results are summarised in the Table 9.29 below.

Mean Overestimate of Predicted Age by Model (years)										
True Age (years)	F SMS	M SMS	F SMS55	M SMS55	F DMS 995	M DMS992	F S&M	M S&M	F CPA	M CPA
1	0.73	0.52	1.52	0.72	0.87	0.48	0.00	-0.25	2.10	1.35
2	0.16	0.04	0.32	0.10	0.26	0.14	-0.02	-0.11	0.52	0.56
3	0.25	0.19	0.03	0.00	0.24	0.22	-0.15	-0.13	-0.01	0.17
4	-0.02	0.02	0.07	0.15	-0.07	-0.06	-0.19	-0.22	0.16	0.44
5	-0.04	0.04	0.23	0.24	0.09	0.15	-0.12	-0.22	0.72	0.88
6	0.34	0.24	0.27	0.22	0.44	0.35	0.14	0.00	0.87	1.01
7	0.32	0.59	0.06	0.33	0.20	0.48	-0.02	-0.08	0.58	1.03
8	0.20	0.07	-0.06	-0.16	-0.03	-0.17	-0.20	-0.33	0.41	0.45
9	0.15	0.10	0.23	0.15	0.30	0.05	-0.15	-0.33	0.68	0.77
10	-0.18	-0.19	0.08	-0.01	0.26	0.02	-0.44	-0.78	0.53	0.70
11	0.18	-0.48	0.45	-0.24	0.67	-0.14	-0.37	-1.16	0.94	0.48
12	0.62	0.09	0.48	-0.07	0.47	0.02	-0.57	-0.98	0.99	0.66
13	0.75	-0.15	0.05	-0.58	-0.13	-0.52	-1.32	-1.34	0.66	0.16
14	1.13	1.09	-0.37	-0.55	-0.72	-0.83	0.80	-0.89	0.28	0.17
15	1.29	0.90					-0.53	-1.52	-0.52	-0.65
16	0.70	0.43					0.13			
17	-0.07	0.11								
Overall	0.36	0.16	0.08	-0.06	0.09	-0.07	-0.25	-0.43	0.57	0.59

Table 9.29: Mean prediction errors (in years) for final regression models, Schour & Massler method (F S&M and M S&M), and for the ages predicted using the published Demirjian conversion tables for DMS to Age (F CPA and M CPA), by age group and overall. F SMS and M SMS are the female and male models respectively, based upon the SMS and the full validation sample dataset. F SMS-55 and M SMS-55 are the female and male models respectively, based upon the SMS and a truncated validation sample dataset. F DMS-995 and M DMS-992 are the female and male models respectively, based upon the DMS and a truncated validation sample dataset.

By way of explanation, the age of female cases in the 1 year-old age group (in the validation sample) is overestimated by a mean 0.73 years when using the F SMS model. Overestimates between the various models are summarised in Table 9.30 below.

t Test statistics* for comparison between models							
	M CPA	F CPA	M S&M	F S&M	M SMS	F SMS	M SMS 55
M SMS	29.80	-	12.08	-	-	4.06	-
F SMS	-	19.61	-	7.83	-	-	-
M SMS 55	67.21	-	13.00	-	4.47	-	-
F SMS 55	-	46.68	-	7.85	-	4.84	3.32

* All significant, p<0.000.

Table 9.30: T-test statistics in relation to overall mean prediction errors for given models.

By way of explanation, the comparison between the overall mean overestimates of age using the M SMS model when compared to the M CPA model yielded a t-test result of 29.80. This indicates that the differences between the two models are significant. It should be also be noted that the initial estimates of age prediction by the selected models were then modified as it became evident that any maturity score beyond the penultimate possible score resulted in potentially misleading, nonsense values. As such the limits of prediction for the M SMS model are 15.5 years and the F SMS model 15.3 years. More detail on this point is provided in the discussion.

The prediction error obtained using the Schour & Massler system in female cases is less than that of the SMS model, while for males it is almost three times greater.

The final preferred models selected are the M SMS-55 and F SMS-55 equations.

9.2.3 Construction of Final Predictive Models

The final regression equations and confidence intervals were derived from the complete truncated dataset and are provided in Figures 9.8 and 9.9 and Table 9.32 below.

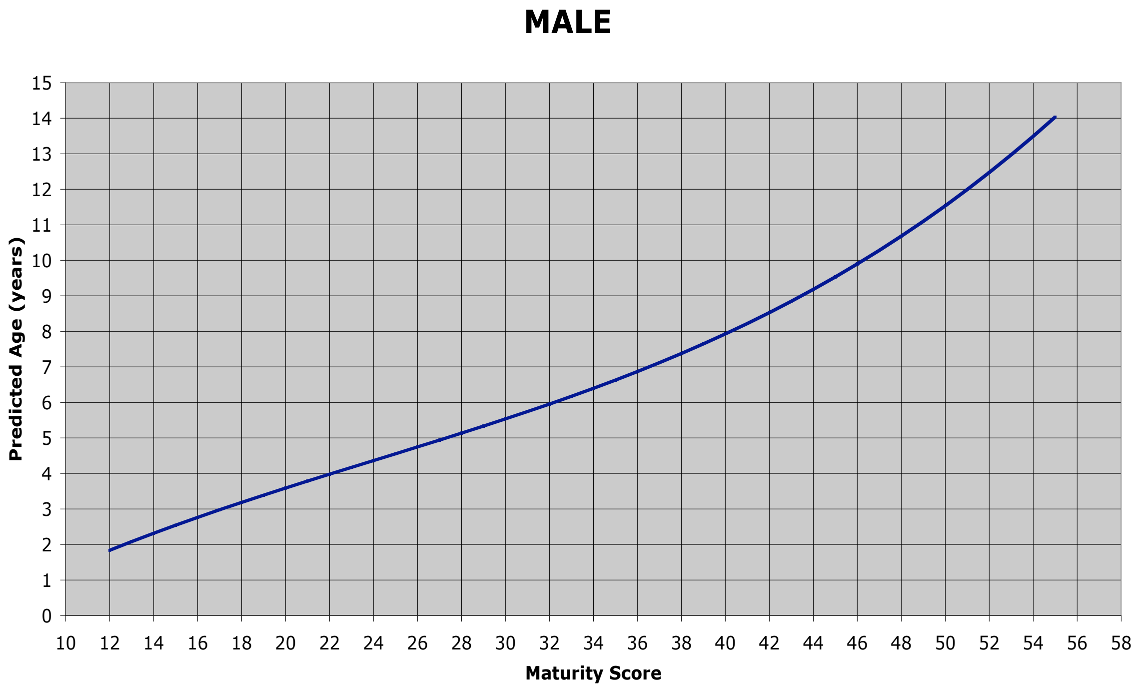

Figure 9.8: Predicted Age against Maturity Score for Males, derived from entire Male sample where n=1363 and $y=-2.042579201+0.416441557*x-0.009307122*x^2+0.000128194*x^3$, where y is the predicted age in years and x is the calculated maturity score.

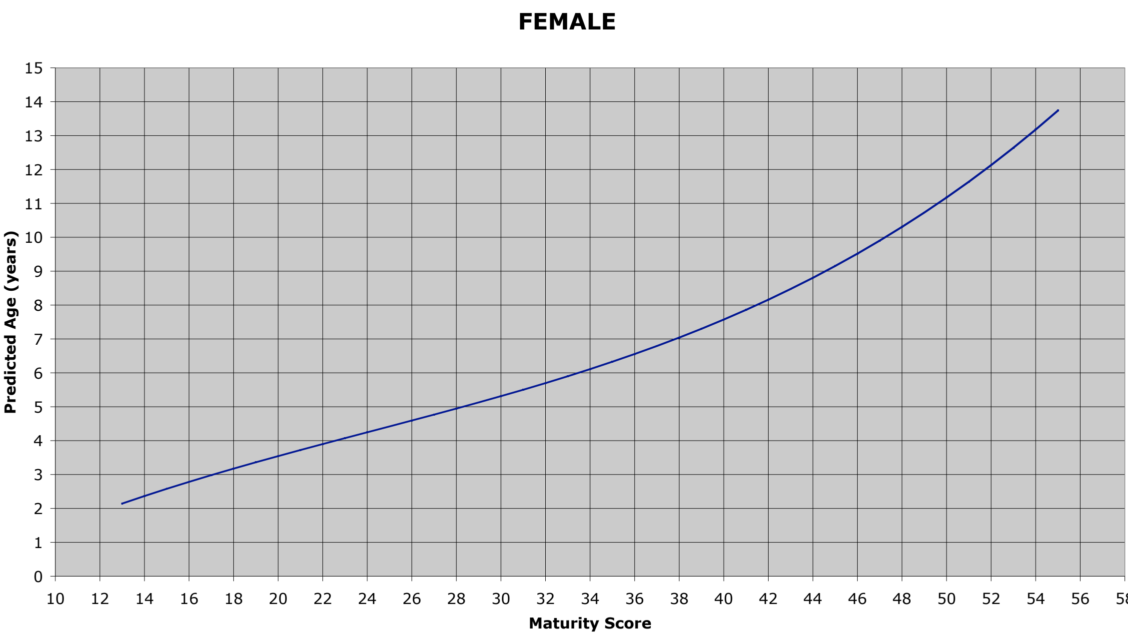

Figure 9.9: Predicted Age against Maturity Score for Females, derived from entire female sample where n=1224 and using the regression formula $y=-1.914675804+0.421823224*x-0.010273636*x^2+0.000141442*x^3$, where y is the predicted age in years and x is the calculated maturity score.

The final regression formulae are:

Male $y=-2.042579201+0.416441557*x-0.009307122*x^2+0.000128194*x^3$

Female $y=-1.914675804+0.421823224*x-0.010273636*x^2+0.000141442*x^3$

The 95% confidence intervals for these final models, by predicted age group, are detailed in Table 9.32 below.

	95% Confidence Interval of Predicted Age (years)	
PREDICTED AGE (years)	**MALE**	**FEMALE**
1	-	-
2	0.70	1.45
3	0.80	0.96
4	0.95	0.95
5	1.38	1.14
6	1.56	1.32
7	1.38	1.41
8	1.68	1.75
9	1.73	2.13
10	1.82	1.89
11	2.21	2.14
12	2.64	2.42
13	2.83	2.62
14	2.58	3.03

Table 9.32: 95% Confidence Intervals (in years) for each age group by sex for the final prediction models (SMS-55). For an age of a male that is predicted within the 2 year age group the 95% confidence interval will be that predicted age ±0.7 years.

The 95% confidence interval, uniform over the entire range of ages and based on the residual error from the ANOVA output is ±1.8 years for both sexes.

Chapter 10

Discussion & Conclusion

10.1 Discussion

This project has demonstrated that the published Demirjian standards are not applicable to an Australian sample of unknown racial composition. Modification of this system, with regression models based on a local sample, resulted in a system with greater accuracy, and therefore, applicability to the Australian sample.

10.1.1 Choice of Method

The Demirjian system was chosen as the method on which to base this Sydney study for a number of reasons. In devising this system, Demirjian theorised that while the pattern of development is reasonably consistent with only minor variations between populations or individuals, it is the rate of development that varies from region to region. For this reason it has been widely used throughout the world, and has been shown to provide an accurate estimate of age when modified to the local population. Most of these modifications have involved either changing the values of the self-weighted maturity scores and/or constructing regression models based on local samples. Both of these changes were made in this present study.

Many studies have reported 95% confidence intervals of ±2 to 3 years for age estimates based on modified Demirjian systems. This error is significantly less than that of other methods, such as those based on the work of Gustafson, wisdom tooth development, tooth attrition, or any of the anthropological measures. This error is also of a similar magnitude to that reported by studies using other tooth development based systems reviewed earlier, such as Moorrees, Fanning and Hunt, Mörnstad, Staaf and Welander, or Liversidge. As detailed in the review, an advantage of the Demirjian system over these latter methods is that with only eight stages it is a simple system to become familiar with, and easy to allocate the appropriate stage to an observed tooth. The stages are well defined, by precise definitions, diagrams, and radiographs. The stages also require that only relative, not absolute measurements be made. All of these factors contribute to a system that has a well reported history of high levels of inter- and intra-observer agreement. The accuracy, reproducibility, and consistency of the Demirjian system, when combined with the lack of requirement for any specialised measuring equipment, made it the method of choice on which to base this project.

The Schour and Massler system was chosen as an alternative system for comparison as it is regularly used at the NSWDOFM.

10.1.2 Inter- & Intra-observer Error

An important feature of any age estimation method is that of reproducibility. That is, where different researchers, or indeed the same researcher on repeated occasions, can obtain the same age estimates for the same cases. The kappa statistics for this study indicate that the level of inter- and intra-observer agreement is 'substantially reliable.' These high levels of intra-observer agreement can be attributed, in part, to pre-calibration training. In absolute terms this present study reports an inter-observer agreement of 70% with an intra-observer agreement of 80%. This differs from the Demirjian study where he reported an inter-observer agreement of 90% (Demirjian et al., 1973). A later study undertaken by Demirjian and Levesque using their previously designed method reported a 75-80% overall level of inter-observer agreement (Levesque and Demirjian, 1980), results more similar to those found in this present study than to those previously reported by Demirjian.

With specific regard to inter-observer error in this Sydney study, the overall level of agreement was found to be 'substantially reliable' with K=0.65. When this level of agreement is broken down and the agreement at each individual tooth is obtained, considerable variation was found between teeth types. This indicates that the development stages of a particular tooth type may be more easily agreed upon than others. Noticeably, the assessment of the stage of development of tooth 47 is remarkably consistent whereas it appears quite difficult to get examiners to agree on the stage of development of tooth 42. So too, it appears that overall some stages of development are more easily assessed than others. It appears easy to consistently identify stages 0, H and A-C, but stages D-G appear more difficult to judge consistently, however this consistency is still rated as moderate. If one examines the interaction of these two phenomena, we can see from Table 9.8 a wide range of reliability when it comes to the level of agreement in the assessment of any stage of development for any tooth. Tooth 42 appears hard to assess consistently in stages D through G, whereas the premolars and molars seem substantially consistent to almost perfect.

Similar observations can be made regarding the intra-observer agreement in this study. The overall level of agreement is considerably higher than that of the inter-observer agreement, but at K=0.80 it is still considered ‘substantially reliable’. Closer examination of this level of agreement revealed some variation between tooth types. This indicates that the development stages of a particular tooth type may be more easily agreed upon than others. However, the range of Kappa values for this variation is 0.71 to 0.85. This indicates that although some teeth are more reliably assessed than others, the level of agreement across all teeth types is at least ‘substantial’ and, in the case of the 44 and 47, ‘almost perfect.’ Again, it appears the lower anterior teeth are the harder to reliably assess. It also appears that, overall some stages of development are more reliably assessed than others. Noticeably, it appears easy to reliably identify stages 0, B and H. In fact, the Kappa values for these stages fall into the ‘almost perfect’ range of reliability. The remaining stages appear slightly more difficult to judge consistently, however this reliability is still rated as substantial. If one is to examine the interaction of tooth type and tooth stage in Table 9.16, a wide range of reliability when it comes to the level of agreement in the assessment of any stage of development for any tooth is observed. Teeth 42 and 43 appear hard to assess reliably in stages D and E, whereas the assessment of the premolars and molars seem ‘substantially’ reliable to ‘almost perfect.’

These results highlight the need to include all teeth in the assessment. While the Kappa values indicate that the assessments of some particular teeth are almost perfectly reliable when it comes to researcher agreement, others are poorly so. From this present study the most likely explanation as to why some teeth are more difficult to consistently assess than others is that it is more difficult to get a clear image of them. The actual tooth position in the mouth results in superimposition of other anatomical structures on the teeth, making it difficult to see the forming tooth clearly. This is very often the case with OPGs where the cervical spine is superimposed on the lower incisors. In order to avoid this superimposition problem, a possible solution would be to use intra-oral radiographs instead of OPGs.

The reasons as to why particular stages of teeth are more difficult to assess consistently than others are more complex, but centre around the qualitative assessment required by the method. The fact that the assessment requires the examiner to qualitatively assess the shape of a tooth and match it to a number of the written definitions for a given stage allows room for variation in interpretation and assessment. As such, it may be difficult for two examiners to agree to fit a tooth to a particular stage, particularly if the tooth in question is at a stage of development very near the borderline between two defined stages. While the rules for the system state that where doubt exists, choose the earlier stage by default, it may well be the case that one examiner may not consider the case borderline – hence a disagreement. Again, this problem is centred on qualitative assessment of the shape and size of the tooth. Demirjian attempted to minimise these problems by refining definitions, detailed diagrams and example radiographic images, but it does still require subjective observations to be made. Even though images are also provided for comparison, the matching of teeth to defined stages was sometimes found to be difficult. As discussed above, this is a problem that other researchers have attempted to address by increasing or decreasing the number of defined stages. Still other researchers have moved towards quantitative measures, such as ratios of crown and root areas, in an attempt to remove the subjective nature of these systems (Kolltveit et al., 1998). It is this latter area that may provide the required solution, however more research is still required.

Despite these shortcomings, the overall Kappa statistics of 0.65 for inter-observer and 0.80 for intra-observer agreement are acceptable in a forensic context. These figures are a good indication that when all seven teeth are used, any overall assessment of development stages resulting in a summative Simple Maturity Score will give a substantially reliable, consistent score. This is so whether the assessments are made by different examiners or by a single examiner over an extended period of time.

10.1.3 Applicability of the Published Demirjian Standards

In assessing the applicability of the Demirjian age prediction tables, it was found that the true ages of children in the Sydney sample were overestimated by overall means of 0.61 years for males and 0.42 years for females.

Overestimates were observed up to 14 years-of-age, but beyond this point the Demirjian system age estimates were well below that of the true age, up to a mean of 2.18 years underestimated in 16 year-old females. The magnitude of the mean overestimates varied between age groups but was as high as 0.97 years in the 7 year-old males and 12 year-old females. These results suggest the French-Canadian children are advanced in dental age by up to one year over Sydney children up to the age of 14, after which point the reverse situation occurs with the Sydney children being advanced over the French-Canadian sample by means of up to 1.2 years for 16 year-old males and 2.2 years for 16 year-old females. These overestimates were found to be significant at the $p<0.05$ level. These results are consistent with findings by McKenna et al. (McKenna et al., 2002), in whose study the same system was used on a sample of South Australian children. It is evident from the results of this present study that the published Demirjian standards are not applicable to the Sydney sample. As such, the first objective, being to assess the applicability of the Demirjian standards to the Sydney sample, has been met. Moreover, in light of McKenna results, the Demirjian standards do not now appear applicable to any Australian sample of unknown racial composition.

10.1.4 The Simple Maturity Score

The Simple Maturity Score was developed for use in later comparisons to predictions based on the self-weighted scores for each tooth described by Demirjian. In the simplified version each additional stage of development scored one extra point regardless of sex or tooth type. Surprisingly, the results of the regression analysis and later examination of the prediction errors demonstrated that the simplified system provided more accurate estimations of age of the Sydney sample than any other models trialed.

10.1.5 Regression Analysis

Many combinations of predictors were trialed in order to find the preferred models. Having completed the regressions, the second objective of developing age prediction models for the Australian population was achieved.

A direct graphical comparison of the truncated models to the full data set models (Tables 9.6 and 9.7) revealed an interesting trend. It appeared that the inclusion of the ultimate high-end scores in the full data set models tends to distort the curve upwards over the last portion of the curve, that is, beyond the final point on inflection. This would affect the accuracy of predictions made on points along this part of the curve. Later examination of the prediction errors confirmed this, with prediction errors of the penultimate ages of the range, being 14 to 16 years, increased significantly over those of other ages. This distortion of the curve over this range may be due to that portion of the curve being 'anchored' at the y-value in the last set of scores (in this case where x=SMS of 56) that minimises the sum of the squares for that set of scores.

Any of the regression models based on the full data set, including those based on the Demirjian self-weighted scores will display the same effect as described in the previous paragraph. As such, one has to limit the upper end of age range which can be predicted to the penultimate Maturity Score (either

DMS or SMS). The reason for this is that once the ultimate score is reached, being all teeth at stage 'H' where the SMS= 56 or the DMS =100, there is no way of knowing if these stages were just attained, or if they were achieved at some time in the past. Unlike lower Maturity Scores, this stage of the teeth does not represent a phase through which everyone will pass - like eruption, it is only an indicator that at some time in the past the final development was completed. As such an 80 year-old will have the same score as a 17 year-old. The more older cases added to the data set, the greater the distortion in the final part of the curve, as the final anchor point increases in y-value, and the greater the prediction errors for those penultimate Maturity Scores. This effect would also have a significant impact on the overall standard errors of estimate, if the final model were based on the full data set. This was not the case, the truncated models, M SMS-55 and F SMS-55 being those finally selected as they provided the least amount of overall prediction error for both males and females – approximately only 10% of the mean overestimate that is obtained using the predictive curves of the Demirjian system (CPA). The main drawback of this model is that the upper extent of the age range covered is limited to 14 years.

For the reasons above, the upper age limits of the models may seem less than reported elsewhere. A significant point that arises from this issue is that if the dentition has finished developing the system is not applicable.

The t-tests show that there are significant differences between the individual male and female models at the $p<0.05$ level (Table 9.30). This difference in models is understandable given the earlier t-tests undertaken in this present study in the examination of sex differences in mean ages for a given score (Table 9.21). In these results it is only the SMS of 45 and 50 that there is a statistically significant difference between the average ages of the males and females. The fact that any significant difference exists at any stage in the development of the dentition is reason enough to rely on separate predictive models for each sex. In light of this sexual dimorphism reported here and in other cited studies, the use of sex-specific models is recommended. In cases where the sex of the remains is unknown, two separate estimates of age should be given, one male and one female.

10.1.6 Comparison Between Systems

Direct comparison of regression models and outputs to the results of the original Demirjian study is not possible for a number of reasons. Demirjian did not publish his original data but instead published manually smoothed curves using a logarithmic scale. As such it was not possible to reproduce the original results of Demirjian for comparison. Further, he described his prediction curves by centile, failing to give confidence intervals which, today, are considered standard format for reporting age estimates in forensic fora. Direct statistical comparison with the results of Demirjian is not possible with only the centile curves available for comparison. These factors have been noted by other authors (McKenna et al., 2002; Teivens and Mörnstad, 2001b).

The solution to this problem in this present study was to examine the mean overestimates of each model when applied to the Australian sample. These overestimates were calculated overall and for each true age group. True age, rather than predicted age, was used as it provided common ground upon which the differing systems could be compared.

The newly derived regression models that gave the smallest mean overestimates were M SMS-55 with a mean of 0.08 and F SMS-55 with a mean of -0.06. These two models were based on the Simple Maturity Score using a truncated sample. These overestimates were significantly less than those of the models based on the full data set (M SMS and F SMS) and also significantly less than those obtained from estimates based on either the original Demirjian conversion tables (CPA) or the Schour and Massler charts. These figures support the view that the SMS models cannot provide a reasonably accurate age estimation beyond the age of 14. That is, one that can be used clinically. Further, most age predictions under the age of 14 can be more accurately derived from the SMS-55 models. Finally, the significant over-prediction as a result of using the Demirjian tables (M & F CPA) is consistent with the earlier results provided on the development sample. All significance tests were undertaken at the $p<0.05$ level. As such, the third objective to test the null hypothesis that the systems would yield the same results, and to choose the model the best predicted ages of the sample, was achieved. The null hypothesis was rejected, and the models M SMS-55 and F SMS-55 chosen as the preferred models.

Of significant note is the fact that for 13 and 14 year-olds, the Demirjian standards (CPA) provide the most accurate estimates of age, displaying the lowest mean prediction errors of any system trialed. It was shown that, for ages 1 to 13 for females and 1 to 12 for males, the SMS-55 models consistently provided far smaller overestimates for each age group when compared to those obtained using the CPA tables. Beyond these ages (14 for females and 13 to 14 for males) the CPA errors were less than those of given by SMS-55. It was in these ranges that SMS-55 errors rose well beyond their mean overall error while CPA errors decreased significantly below their mean overall error. It may well be significant that it is at about this age that Australian children become advanced in dental age over the reference sample. This finding is consistent with those found earlier in the study regarding the relative position of dental maturity rates between the two countries, and also with the findings of McKenna et al. If the Australian children are retarded in dental maturity compared to the French-Canadians up to about 14 years at which point dental maturity of the Australians becomes advanced over that of the French-Canadians, it is conceivable that at some point the dental maturity of both groups will be about the same for a given chronological age. It is at this point, the cross-over period, that the Demirjian French-Canadian conversion tables (CPA) will most accurately estimate Australian ages. This explanation thus describes why it is within the 13 to 14 year age groups that the prediction errors obtained using CPA are equal or less than those of the locally derived models. As far as clinical application is concerned, it is not necessary to swap between systems and use CPA for 13 and 14 year-olds. To do this would be time consuming as the different versions of the maturity score, DMS and SMS, would both have to be calculated. Also, the difference in overestimates between the two systems at this cross-over period is, at most, 4.6 months. Given the overall confidence intervals for these models of 2-3 years, the discrepancy between the two systems may not be clinically significant. However, noting that CPA will accurately predict Australian age for 13 and 14 year-olds, it could be used to double check any such estimates made using the SMS-55 models.

T-tests could have been conducted on the results of the overestimate calculations to ascertain whether or not a given models' predicted ages were significantly different from the true ages of the population. This was not undertaken, as any significant difference that arose would have been due to flaws in the randomization in the sampling process, that is, a true type I error. Given that the sample was one of convenience, the likelihood of this occurring was high. This is an area that should be further investigated in future studies.

10.1.7 Chosen Models

The final selected models, being that of M SMS-55 and F SMS-55, are applicable for the defined age range of 2-14 years. A description of the use of these models is provided in the results chapter. With the construction of these final models, the fourth and final objective of this study has been achieved. Larger versions of these charts are in Appendix B.

It is the intention that these models be used at the NSWDOFM to assess the age at time of death of remains that are recovered where the identity of the individual is unknown. In cases where the remains of a child are recovered and the identity of those remains is unknown, it is usual practice to refer to the police missing persons database to search for a putative identification. With over 6000 persons reported missing annually in NSW alone, the search for a putative identification is significantly expedited if a physical profile of the patient can be established. Such details would include age, height, sex, and possibly race. In this way, the field of missing persons to search for a possible match can be narrowed to that group that approximates this physical profile. When dealing with children and adolescents, sex and age at time of death are often the most effective tools in narrowing this field. As with all other methods of age estimation it is recommended that any estimations of age using these models be corroborated with at least one other method.

Another intended application of these models is that of establishing relative age at time of death of a number of sets of remains. Occasionally the situation will arise where two or more sets of remains from children killed in the same incident will be recovered simultaneously. If the bodies cannot be visually identified for reasons such as burning, decomposition or skeletonisation, it may fall to other methods to discriminate between them. This is the case even in situations where the putative identifications of those in the group are known. Direct identification by dental record comparison is sometimes not possible with children, due to factors such as little or no dental treatment for comparison, and the rapidly changing physical profile of the dentition that occurs during growth. By using the models derived in this Sydney study, one can provide an estimate of age of time of death for each set of remains. Using these estimates, or even by comparing the raw Simple Maturity Scores, one may be able to establish the relative stages of dental maturity of each set of remains, thus providing the means to discriminate between them.

10.1.8 Description of Confidence Intervals

The calculated 95% confidence intervals for both sexes, up to about 11 years-of-age are similar to, or smaller than, those reported in the studies reviewed earlier. While the reported 95% confidence intervals for the other methods range from ±1 year to ±20 years, those based upon the development of the dentition average about ±2 years. It is only for the ages 12 to 14 years that the confidence intervals for the models developed here rise above those in other studies. Even then it is only up to a maximum of ±3.03 years for 14 year-old females. This increase in the magnitude of the confidence intervals in the older age groups is consistent with reported results, in this and other studies, that indicate that the range of natural individual variation of dental maturity increases with age. As such, the selected models in this present study do more accurately predict age in the younger age groups.

10.1.9 Biological Variation in Dental Development

It was initially intended to examine the mean age of attainment for each stage for each tooth. This goal was unachievable for two significant reasons. Firstly, teeth are observed in a certain stage of development but the exact age at which they reached that stage is unlikely to be observed. Much like eruption, 'age of attainment' of a given stage of development is a fleeting moment. All one can say, having observed that a tooth is at a specific stage of development, is that stage was reached at sometime previously. The second confounding factor is that these stages last for a period of time, the length of which is subject to normal biological variability. As such, defining an 'age of attainment' is subjective and will not provide much in the way of useful information. An alternative approach would be to provide an age range during which period a given stage is observed, much like the work of Fanning (Fanning, 1961). This information would prove useful in a general clinical setting and as such warrants further investigation. In this study, however, the aim of examining the variation was to place the magnitude of prediction errors in context. In order to achieve this aim, the variation of the developing dentition as a whole was examined by comparing the overall measure of dental maturity, the Simple Maturity Score.

Figure 9.1 depicts the variation that was observed in ages for a given maturity score. That is, owing to biological variation in the population, different children will attain a given stage of development at different chronological ages. The results here show that this variation is between 1 and 2 years up to about 9-10 years-of-age, beyond which the variation increases up to as much as 4 years for a given stage of dental maturity. These results are consistent with those reported by other authors (Garn et al., 1959; Mörnstad et al., 1994b). Garn also observed that there is more variation in later forming teeth than in the earlier forming ones. Nykanen and Liversidge both noted that the later stages of development of each tooth last for a longer period of time (Liversidge et al., 2003; Nykanen et al., 1998). Given that the later stages of tooth development span a greater period of time, this would allow greater scope for variation during this time. In considering these points it is not surprising that the observed variability, in this present and other studies, is greater in the older age groups.

No results were discarded on the basis of being considered 'outliers'. While some results were at the extremes of the variation range, these were retained. The reasoning behind this decision was that, if they were observed and truly did have those levels of dental maturity recorded, then they were valid values.

If the average reported overall natural range of variation in dental maturity for 95% of the population is about ± 1.5 - 2 years (Mörnstad et al., 1994b), with which the findings in this present study are consistent, it follows that it is not possible to predict age of a child any more precisely than this, if methods based on tooth development are to be used.

10.1.10 Global Variation in Dental Development

In light of the studies reviewed earlier in this treatise, it is apparent that much of the variation in dental maturation is due to genetic heritage. Historical, but also recent world trends, such as the availability of affordable and efficient intercontinental transport and less restrictive immigration policies in many regions, have lead to ever increasing levels of population mobility. This has led to further intermixing of gene pools resulting in less distinct racial groups. Most studies involving dental development have aimed for a racially homogeneous sample in the hope of limiting the variability in dental maturation rates. This may not be possible, as indicated by the Nyström findings that revealed that significant variation can even exist within what was thought to be a ‘fairly homogeneous’ population (Nyström, 1988).

The impact of these observations on this present study is that if there are significant variation in rates of dental development between countries, and that Australia has a significant proportion of its population from many other countries, then the variation within an Australian sample may well be much larger than those ranges reported from countries with less genetically mixed populations. If the variation is greater, then so must be the confidence intervals for any predictive models based on a random Australian sample. This may well account for the range in the confidence intervals that were calculated for all groups in all models, but particularly the larger range in the older age (16 to 17 years) groups.

This multicultural nature of Australian society means that unless the genetic or racial origin of the victim is known and the appropriate conversion tables for that specific group can be used, we shall have to rely on standards that are based on random samples of the population. As discussed above, such standards will give a larger range of error for any given age estimate. However, being based on a potentially racially heterogeneous sample, this estimate and error will be appropriate. This present study has produced such standards.

10.1.11 Limitations

a) Sampling considerations

The majority of cases examined at the NSWDOFM arise from the Sydney metropolitan area. If the age estimation models are to be used at the NSWDOFM with any degree of certainty, it is the population of this region that they should be based on. A random sample of the Sydney population was initially thought to be desirable, but obtaining it not practical. The issue was further complicated by the problem that, in order for the sample to be a valid representation of the Sydney metropolitan area there was a need to have sufficient children of different national origins. It was equally important to obtain a reasonable number of both males and females in all age groups, and that each age group have the representative proportion of racial groups reflected in the Sydney population. In a study of somatic and skeletal growth of Sydney children, Jones, Hemphill, and Meyers stated that a random sample of the Sydney population may not provide the representative sample described above (Jones et al., 1973). Jones, Hemphill, and Meyers found that while census figures showed what 'racial groups' were represented in the population, no indication of the distribution by age group was provided. Similar problems were encountered in this present Sydney study, in addition to the problems faced when attempting to define racial groups.

Identifying the proportion of the population belonging to specific racial groups is not easily done. Australian census information only lists ‘country of birth’ and ‘country of birth of each parent’ (Australian Bureau of Statistics, 2001) - neither of which is necessarily indicative of racial origins. The multicultural nature of the Australian and other populations is such that this information may not be useful in identifying groups of different racial or genetic heritage. This problem was borne out in a recent study by McKenna et al. (McKenna et al., 2002). Their study, conducted on a racially diverse South Australian sample, found that where age prediction errors occurred, no significant differences existed between Australian-born children with parents of Australian birth and those with one or both non-Australian parents.

While it may be difficult to identify proportions of population substructure, other problems existed in identifying racial origin of the cases selected. 'Race' is not a detail contained in the public system dental records, only 'country of birth' is recorded. In the majority of cases this was listed as Australia. In light of the diverse multicultural population of Australia, this answer is often not an indicator of racial background. One possible solution to this lack of information is the examination of surnames. A number of studies have been successfully undertaken in an attempt to accurately ascribe racial identity using surnames (Howard et al., 1983; Nicoll et al., 1986). Unfortunately, these studies have been undertaken on a limited range of racial groups, and as such do not cover the diverse range of racial backgrounds found in Australia today. For this reason this technique was not used in the present study.

Despite the lack of available information on racial heritage, a racially heterogeneous sample was sought. In light of the sampling requirements, it was important to have these groups selected from all over Sydney for the sample to be a representative one. An attempt to address these issues was made by obtaining samples from two dental hospitals (Westmead and Central Sydney) and three other school-based dental clinics (Daceyville, Dee Why and Marrickville). These sites were chosen partly for availability of access to the dental records and partly to obtain samples from a broader cross-section of the region, in the hope of obtaining a more racially diverse sample.

It was the initial intention to randomly select dental records from the above sites. In practice, all available dental records at each site were used to obtain the required sample sizes. Further, the records at each site that contained the required radiographs were neither a true random sample of all the children in the area, nor of all the children treated by the clinic. Upon examination of patient files it appeared that most of the OPGs were taken for either orthodontic or pre-surgical assessment, providing a potentially biased sample of treated patients. Finally, a number of records were excluded from this study for the reasons detailed in the Materials and Methods section. Therefore, a random sample of available records was not taken; instead, it was one of convenience.

Taking into account the above sampling issues and exclusions, it is evident that the sample used is neither a true random sample nor is it necessarily a true representation of the Sydney metropolitan area.

b) Other systematic sources of error

In addition to those discussed above, other potential sources of error in this Sydney study have been identified. These areas should be addressed in any additional research based upon any findings of this study.

While the author and other examiner responsible for the analysis of the OPGs were blinded as to the age of the cases, the information was available to them. The chronological age of the individual at the time that the OPG was exposed was calculated by subtracting the date of birth of the child (DOB) from the date of OPG exposure (DOX). Date of birth was usually contained in the patient file, and date of OPG exposure was always found on the OPG film, but occasionally both details were printed on the film. Having both the patient file and OPG together at any one time, or working on a film on which both pieces of information were printed, prevented the true blinding of the study. As detailed in the Methods section of this treatise, the calculation of true age from date of birth and date of OPG exposure was not undertaken until after the OPGs were analysed for stages of development. Therefore, in this present study, while not truly blinded, the assessors were effectively blinded as to the true age of the cases being assessed.

The mathematical calculation of age from maturity score (DMS) in the Demirjian system is not possible. Demirjian provided no raw data on which his estimates were based, the curves on his conversion charts were hand fitted, and no regression formula was published. Therefore, in this present study in order to calculate Canadian Predicted Age (CPA) from a given

Demirjian Maturity Score, the conversions were based on a visual assessment of CPA as read from the published charts of Demirjian. As such, this provides a potential source of error in these predictions, which would then have an impact on any comparison made to age estimates from other models.

The dental records examined contained no record of whether preterm birth or low birthweight, had occurred. Studies have shown that this can have a significant impact on dental development, delaying maturation of the permanent dentition by up to 6 months in children under 6 years-of-age (Seow, 1996). As such, this information, had it been obtained, could have been used to adjust the ages to account for the preterm birth. This would have provided a more accurate reflection of the 'age' of any affected cases and possibly resulted in less variation in the sample.

10.1.12 Future Directions

If the models produced in this Sydney study are to be used in the forensic setting, validation studies need to be undertaken. For use at the NSWDOFM it is recommended that the models be validated on a representative sample of the Sydney population. Should this validation prove the effectiveness of the models, it would be appropriate to undertake further validation studies on representative samples of other major urban centres. This would allow for the wider use of the models within Australia if appropriate.

It is debateable whether further consideration should be given to a method that will enable better discrimination between the diverse racial groups that make up a significant proportion of the Australian population, in order to provide a truly representative sample. Any attempt at such an endeavour may prove futile as gene pools continue to mix as rates of immigration and 'inter-racial breeding' increase. The characteristics of racial groups, and the lines of genetic heritage become less distinct over time.

An alternative approach to adapting the Demirjian system to a Sydney population may also be undertaken. Whereas in this present study the Simple Maturity Score (SMS) was devised as the basis for the preferred models, an alternative maturity score may provide estimations that are more accurate. Willems et al. undertook such an approach in their study on Belgian children previously cited (Willems et al., 2001). This method would involve taking data from a large sample analysed according to the Demirjian system, then performing a weighted ANOVA with all seven teeth as covariates for males and females separately. In this way new weighted scores for each stage of each tooth are derived. These new individual scores can then be attributed to a case according to the stages of development present, and added together to give a new Maturity Score. This new Maturity Score could then be converted to an estimate of age using the Demirjian standard curves. Again, as with this present study, the racial constitution of the sample would be critical in determining the extent of the application of such a model.

A recent study by Chaillet et al. (Chaillet et al., 2004) used Goldstiein's method as used by Demirjian et al. (Demirjian et al., 1973) to derive population specific self-weighted scores. At the time that this present Sydney study was undertaken, correspondence from Professor Goldstein indicated that the software required for the derivation of population specific self-weighted scores was no longer available (Goldstein, 1999). As this no longer appears to be the case, this present study could be repeated using such software to derive these scores for a Sydney sample. Following development of new regression models, the accuracy of such models could be compared to the results provided here.

10.2 Conclusion

This Sydney study sought to ascertain whether the Demirjian, DMS based system could be improved upon, with the ultimate aim of enhancing its applicability in the clinical forensic setting of the New South Wales Department of Forensic Medicine, Glebe. In order to achieve this aim, the four objectives as detailed in the introductory chapter were pursued and achieved.

The standards of Demirjian system, being based on a French-Canadian sample, were not found to be applicable to the Sydney sample. The use of these standards resulted in consistent overestimates of chronological age in children under the age of 14 years by as much as a mean of 0.97 years, and underestimates of chronological age in children over 14 years by as much as a mean of 2.18 years in 16 year-old females. These results are consistent with another Australian study (McKenna et al., 2002) and indicate that the mean rate of development of the Australian samples is significantly different to that of the French-Canadian one. The use of the Demirjian standards to estimate chronological ages of the cases from a Sydney sample provided consistently inaccurate estimates, and is not recommended for use on any Australian sample.

Despite the lack of applicability of the standards of the Demirjian system to the sample, the underlying system of defined stages proved sound. The observed levels of both inter- and intra-observer agreement were high and similar to those reported in other studies that used the defined stages of development of the Demirjian system. These results were not surprising, for two reasons. Firstly, in this present study, the stages as defined by Demirjian, were not modified in any way. This provided a level of commonality between this and other studies. Secondly, the use of pre-calibration training as recommended by other studies was undertaken.

A range of alternative predictive models were derived from the Sydney sample. The models of choice, being those that provided the most accurate age estimates, are applicable for the age ranges 2-14 years with a coefficient of determination value of R-square=0.94, and a 95% confidence interval varying from ±0.7 to ±3.03 years, depending on the predicted age. This exercise has shown that by basing models on a sample to which they will be applied, a reliably accurate estimate of age can be obtained.

The null hypothesis that age estimates based on the standards of the Demirjian system are the same as that based on modifications of the system, or other systems, was tested and found to be false. The SMS based models derived in this Sydney study were found to provide estimates of chronological age that were significantly different to those of the Demirjian model. Further, the SMS based models provided better estimates of chronological age of the sample population than those obtained using the Demirjian DMS based model. These findings further support the recommendation that the use of the Demirjian model on an Australian sample is inappropriate.

With regard to the limitations of this Sydney study, sampling considerations have been highlighted as paramount. The review of the literature indicates that genetic heritage is the single most important influence on rate of dental development. If the genetic heritage of the case in question is unknown, or even if the case derives from a multiracial society, this important factor cannot be accounted for, in the models used and developed in this study. As such, models should be constructed that allow for the wider biological variability inherent in a racially diverse, or multicultural, population by basing any such model on a truly representative sample of the population to which they will be applied.

This present study has attempted to achieve this. Models were produced that provided more accurate estimates of chronological age than those of existing standards. These models were based on a potentially racially heterogeneous sample. Whether or not this sample was representative of the Sydney, or indeed the Australian, population will only be confirmed by further validation studies. However, it has been shown in this Sydney study that the Demirjian system can be improved upon.

Recommendation

It is recommended that, following further validation studies on Sydney samples, the final predictive models developed in this study be used at the NSWDOFM in preference to the Demirjian standards.

Chapter 11

Age Estimation using SMS

In order to use the SMS system, post-mortem radiographs of teeth 41 to 47 or 31 to 37 need to be taken. One must assess the stages of development of teeth 41 to 47 (or 31 to 37) and assign each tooth a specific development, according to the eight defined stages of the Demirjian system. The stages are then converted to numerical values 1 through 8 according to the Table 8.4. These values are then totalled to give the Simple Maturity Score (SMS) for that case. A predicted age can then be read off Figures 9.8 or 9.9 depending on sex.

The more conservative approach to describing the confidence intervals of these estimates is as follows. Essentially, it involves the use the uniform 95% confidence interval of ±1.8 years (described above) for all predicted ages where the confidence intervals calculated by age group in Table 9.32 fall below this value. That is to say, for males up to the age of 9 years, use the 95% confidence interval of ±1.8 years, for ages 10 to 14, use the 95% confidence interval figures quoted in Table 9.32; and for females up to the age of 8 years, use the 95% confidence interval of ±1.8 years, for ages 9 to 14, use the 95% confidence interval figures quoted in Table 9.32.

Once this predicted age is obtained, the corresponding 95% confidence interval can be given by referring to Table 9.32 and/or the figure of ±1.8 years, as appropriate. For example, a male with an SMS of 36 gives a predicted age of 7 years (from Figure 9.8). Being below the male threshold of 9 years, the 95% confidence interval for this estimate is age ±1.8 years, giving the final estimate of age as 7±1.8 years. A female with an SMS of 52 gives a predicted age of 12.2 years (from Figure 9.9). Being above the female threshold of 8 years, the 95% confidence interval for this estimate is age ±2.4 years (from Table 9.32), giving the final estimate of age as 12.2 ±2.4 years.

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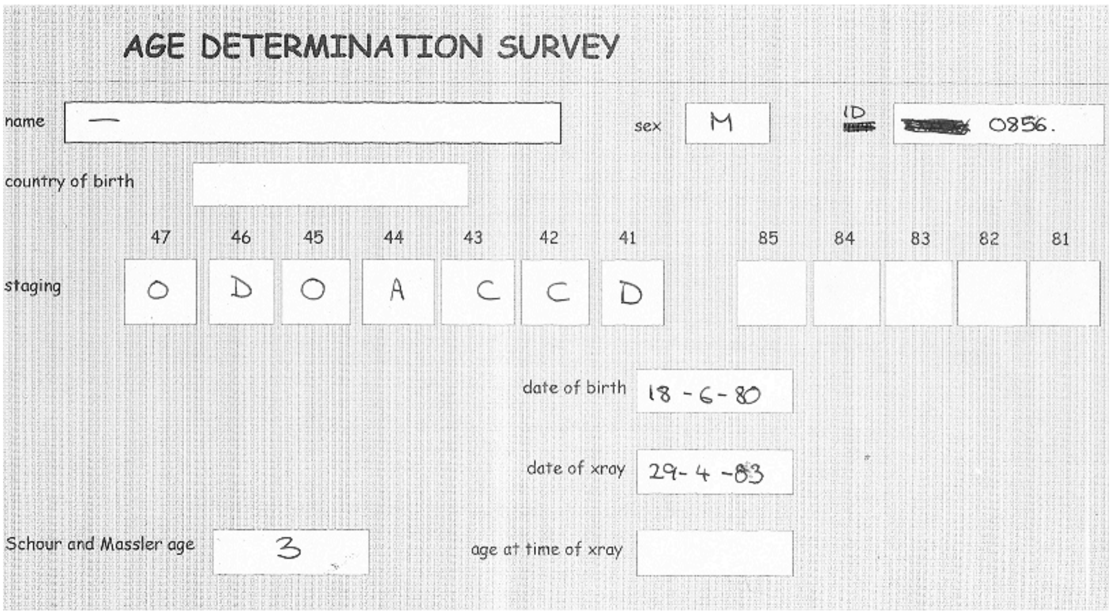
APPENDIX

A1 Data Sheet

Below is an example of the data sheet used to record the details of the analysis of the stages of development of each tooth 41 to 47 from each OPG.


AGE DETERMINATION SURVEY

name: —
sex: M
ID: [redacted] 0856.
country of birth:

	47	46	45	44	43	42	41	85	84	83	82	81
staging	O	D	O	A	C	C	D					

date of birth: 18-6-80
date of xray: 29-4-83
Schour and Massler age: 3
age at time of xray:

Figure A1.1: Sample of data sheet used to record assessed stages of tooth development, sex, date of birth and date of OPG exposure for each case. Each box labelled 47 to 41 represents the assessed level of development for the given tooth (FDI notation).