DOCTOR OF PHILOSOPHY

Investigation of Photographic and Digital Methods for Odontological Comparison to aid with Human Identification

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Investigation of Photographic and Digital Methods for Odontological Comparison to aid with Human Identification

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List of Abbreviations

2D	2-dimensional
3D	3-dimensional
ABFO	American Board of Forensic Odontology
AM	Ante-mortem
AutoIDD	Automated Identification from Dental Data
BAFO	British Association for Forensic Odontology
CAD-CAM	Computer Aided Design – Computer Aided Manufacturing
CBCT	Cone Beam Computed Tomography
CFS	Craniofacial superimposition
CT	Computed Tomography
DNA	Deoxyribonucleic acid
DSLR	Digital single lens reflex
DVI	Disaster Victim Identification
FOs	Forensic Odontologists
ICC	Intra-class correlation
ICP	Iterative Closest Point
DICOM	Digital imaging and communications in medicine
MRI	Magnetic Resonance Imaging
INTERPOL	International Criminal Police Organization
IOS	Intra-oral scans
PET-CT	Positron Emission Tomography
JPEG	Joint Photographic Experts Group
MSc.	Master of Science
NHS	National Health Service
NPIA	National Policing Improvement Agency guidance
PCA	Principal Component Analysis
PI	Principal investigator
PM	Post-mortem
PMCT	Post-mortem computed tomography
RMS	Root mean square
STL	Stereolithographic
TIFF	Tagged Image File Format
VC	Visual comparison

List of Publications, Conferences and Workshops

Research Publications:

- Reesu, G.V., Woodsend, B., Mânica, S., Revie, G.F., Brown, N.L. and Mossey, P.A., 2020. Automated Identification from Dental Data (AutoIDD): A new development in digital forensics. *Forensic Science International*, *309*, p.110218. https://doi.org/10.1016/j.forsciint.2020.110218

- Reesu, G. V., Manica, S., Revie, G. F., Brown, N. L. & Mossey, P. A, Forensic dental identification using two-dimensional photographs of a smile and three-dimensional dental models: a 2D-3D superimposition method. *Forensic Science International – In Review /* ***Revision*** - FSI-D-20-00118.

Achievements:

- **1st Prize for Best Poster Presentation,** Postgraduate Research Dental Symposium, School of Dentistry, University of Dundee, May 2018.
- **2nd Prize & Cash Award for Best Scientific Paper Presentation,** British Association for Human Identification (**BAHID**) Conference, **Manchester**, UK, December 2018.

Conference presentations:

- **Scientific Paper Presentation,** American Academy of Forensic Odontology (**ASFO**) Conference, Anaheim USA, February 2020.
- **Scientific Paper Presentation**, British Association for Forensic Odontology (BAFO) Conference, Sheffield, UK, November 2019.
- **Key Note Speaker** at the 17th National Conference of Indian Association of Forensic Odontology (IAFO), New Delhi, India, September 2019.
- **Scientific Paper Presentation**, American Academy of Forensic Odontology (ASFO) Conference, Baltimore USA, February 2019.
- **Scientific Paper Presentation,** British Association for Forensic Odontology (BAFO) Conference, Cardiff, UK, October 2018.
- **Scientific Paper Presentation** at Scottish Oral Health Research Collaboration Research Programme, Glasgow Dental School, Glasgow, January 2018.
- **Poster Presentation,** British Association for Forensic Odontology (**BAFO**) Conference, **Newcastle**, UK, November 2017.

Workshops Conducted

- Conducted Forensic Odontology Workshop titled **Oral Autopsy – A Practical Approach** at the 17th National Conference of Indian Association of Forensic Odontology (IAFO), New Delhi, India, September 2019.
- Conducted Forensic Odontology Workshop at **British Undergraduate Dental Research** Conference, Manchester School of Dentistry, March 2017.

Contribution to Research

The research as described in this thesis will offer the following contributions:

AutoIDD Software

- ✓ This new automated software will be mabe available as a free and downloadable application to all users through a research website soon.
- ✓ This software is compatible on a windows laptop/desktop or mac operating system.
- ✓ Interested researchers can use this application for further studies.

2D-3D superimposition

- ✓ A user manual will be made available for this method through the website for technical guidance on hands-on application with the Rhinoceros software.
- ✓ Researchers can test this technique using photographs and selfies in their studies.

Acknowledgement

This research has been truly challenging and would not have been possible without the encouragement and enthusiasm of many people. First and foremost, I want to express my sincere gratitude to my supervisor Professor Peter A Mossey for his time, patience and supervision during this research. I am grateful to his kind and extended guidance during many late hours of the day. I would like to thank Dr. Scheila Manica for her support and encouragement through all these years.

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My special thanks to Kelly Urquhart and Jillian Sutherland, for their endless support and extended efforts in many occasions and heartfelt encouragement. Many thanks to Dr. Gavin Revie for his assistance with the statistical analysis for this research and for those valuable inputs and thoughtful discussions. I am also thankful to Scott McGregor, our librarian for his prompt support and encouragement during these years.

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I am fortunate to have been surrounded by few colleagues and school staff who cared for my well-being!! I also thank Sally and Maxi for their everlasting love and affection. Finally, my special thanks go to my family and friends who have supported me unconditionally throughout my career and over the last 4 years.

Certificate

I certify that this thesis is the original work of **Gowri Vijay Reesu.** The condition of the relevant Ordinance and Regulations of the University of Dundee for the degree of PhD have been fulfilled.

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Declaration

I, **Gowri Vijay Reesu**, hereby declare that I am the author of this thesis and that all references cited have been consulted by myself. The work in which this thesis is a record, has been done by myself and that this work has not been previously accepted for a higher degree.

Gowri Vijay Reesu

Dedication

I dedicate this research in memory of my father Gowri Prasad Reesu,

To my loving wife Garima Arora,

To my dearest friend and mentor Nathan Brown for making this dream possible and who stood beside me and urged me at every step of the way,

With love and gratitude to my family for their extraordinary commitment towards my education.

Abstract

Comparative dental identification may be the most efficient and cost effective means of scientific human identification methods when compared to fingerprint and DNA. Standard forensic odontology techniques for identification are usually unsuitable in cases where the ante-mortem dental records of the victim are not available or inadequate for forensic identification. Photographs of the person smiling may provide valuable information. In such cases, teeth can be used in a successful identification process if the AM photographs show visible anterior dentition that is also present in the post-mortem remains for analysis. There are no reported studies that have investigated the reliability of a superimposition method using 2D photographs of a smile and 3D dental models in dental identification. The application of 3D imaging has not been explored or utilised to its full potential in forensic dental identification. Hence, a study was designed with an aim to explore novel odontological methods by combining 2D photographs with 3D models by simulating a dental identification scenario. The objective was to see if 3D imaging in the field of forensic odontology can assist with human identification as an alternative to multiple PM photographs. The study comprised a total data of 70 digital photographs of the subjects smiling and 62 3D dental models. This study was conducted in two dental identification scenarios: Scenario A and Scenario B. Each scenario was analysed in two phases: Phase I- Visual Comparison of 2D-3D images and Phase II- 2D-3D Superimposition, both methods by the principal investigator (PI). One third of the sample was evaluated by six raters (three experienced forensic odontologists and three MSc. students). This method allowed analysis of the front teeth with emphasis on teeth alignment and morphological features. The inter-rater agreement was assessed using intra-class correlation (ICC 2, 1, absolute). The results of the study suggest that the inter-rater and intra-rater reliability using 3D superimposition was highest (ICC ≈ 1.0). In summary, this study demonstrated that dental comparison was better using 3D PM

technology compared to 2D PM comparison. There was an increase in dental match rates and higher certainty among the opinions reached when using the 2D-3D superimposition method. This method also attempted to reduce the limitations of previously reported methods.

Following the results of the above study, the second study focussed on integrating 3D imaging with 2D selfies and to evaluate its feasibility in dental identification using photographs. A pilot study was designed and conducted by the PI in a similar way to the photographic superimposition study using 2D-3D method. The sample consisted of ten 3D scans obtained from the study participants (aged between 25 to 55 years) by the PI. Each participant also provided three selfie images taken from their smartphone within a year where one image with a smile was used for analysis. Two additional non-matching selfie images were included with the ten 2D selfies. The results indicated a change in conclusions by the PI. The lack of inter-rater agreement was a limitation to this study. The role of smartphones can be significant, and a selfie or photographic identification in the area of forensic odontology would be identified as an emerging alternative to conventional methods. Future studies should focus on large sample size with various selfie angulations.

The application of 3D technology in dentistry has widely expanded in recent years and several 3D imaging systems have been developed for scientific and clinical research. A review of various semi-automated 3D systems showed that the applicability of 3D superimposition and evaluation has increased. However, it appeared that most software does not have automated features which facilitate in the automated superimposition process. Hence, an experimental study was conducted to test the performance of the GOM Inspect software for automated identification using multiple 3D dental models. It was found that the software was unable to perform an automated identification with multiple 3D datasets and required manual intervention for comparison. In a forensic context, this software may be useful in single case identifications but not suitable for multiple case scenarios. There is a need for a new automated software that overcomes the limitations of this software.

There are no reported studies which presented a fully automated software that would align 3D dental models and / or scans and identify the correct match from a large dataset. This led to the design and development of a new automated software named AutoIDD which can process large datasets of 3D dental models. This software was tested using full arch post-orthodontic 3D dental models to determine the performance of the software in identifying the correct 3D dental model matching pairs which were obtained from the same patient. The testing was successful as the target scans were accurately identified from a large dataset with similar dental patterns.

The availability of AM 3D data has potential to allow for digital comparison with the PM 3D data which can be applied in dental identification cases. With the encouraging results from the software testing, a study was designed to evaluate the functionality of the AutoIDD software using 3D intra-oral scans (IOS) data from a prospective sample for validity and reliability. The total study sample consisted of 120 3D maxillary and mandibular dental data. To reconstruct a dental identification scenario, 30 maxillary and 30 mandibular dental arches scans were obtained using 3Shape TRIOS Intra-oral Scanner by the PI and were considered as IOS-AM. After one year, another set of IOS (60) were acquired from the same participants and were considered as IOS-PM.

To conclude, the AutoIDD software was able to successfully demonstrate the identification of correct matches with a match percentage that clearly differentiates the matches from non-matches. This software also enabled recognition of the changes in the human dentition, such as restorations and missing teeth. Further research and software development is required in the investigation of pre- and post-orthodontic samples, partial dental remains (jaws) and single tooth PM 3D models.

Research Overview

This research consists of nine chapters. At the inception of this research, the comparative dental identification was well established in the field of forensic odontology. Hence, Chapter 1 was briefly about the background of this research, application of 3D imaging to photographs in forensic dental identification and the potential for a feasible automated dental identification system along with proposed methods of approach.

Chapter 2 reviewed the literature on key aspects related to the field of forensic odontology, such as the importance of accurate dental records, uniquenss of the human dentition, clinical and forensic photography, 2D imaging and the application of 3D imaging.

Integration of 3D technology to 2D photographs of smile was demonstrated through a 2D-3D superimposition method in Chapter 3. Based on the findings of the 2D-3D methodology, a pilot study was conducted using selfies in Chapters 4.

A review of various semi-automated systems employed in dental research along with an experimental study using an industrial software in Chapter 5 necessitated towards the development of a new automated software and testing of 3D models for automated alignment and identification in Chapter 6.

Following the successful testing of the new software, a study was designed and conducted to determine the functinality of the software using 3D IOS in Chapter 7. This research was concluded with future recommendations in Chapter 8 and 9 respectively.

Chapter 1 - Introduction

1.1 Background

Forensic odontology was defined as “proper handling and examination of dental evidence, in the interest of justice, so that the dental findings may be properly presented and evaluated” (Keiser-Nielsen, 1967).

It has four major areas of activity, namely: (1) the examination and evaluation of injuries to teeth, jaws, and oral tissues resulting from various causes, (2) the examination of marks with a view to the subsequent elimination or possible identification of a suspect as the perpetrator, (3) the examination of dental remains (whether fragmentary or complete, and including all types of dental restorations) from unknown persons or bodies with a view to the possible identification, (4) Age estimation from the dentition, including radiographic analysis of root formation of teeth. This may be for living patients (usually to assist courts in determining whether the individual is an adult or juvenile), or for the deceased to assist with identification (Keiser-Nielsen, 1968, Keiser-Nielsen, 1977, Willems, 2001, AlQahtani, 2008).

Forensic odontology has been designated as one of the three primary identifiers by the International Criminal Police Organization (INTERPOL) by which identification can be confirmed. The other two identifiers are ‘Friction Ridge Analysis’ (fingerprints) and (human genetic material) ‘DNA’ (INTERPOL, 2018). Human identification through dental remains is a well-established and reliable method (Rothwell, 2001). Dental identification may assume a primary role in the identification of remains when other primary identifiers (fingerprint and DNA) methods are not feasible (Avon, 2004).

Accurate human identification is of utmost importance for humanitarian, legal, social and forensic reasons, thereby bringing closure to the surviving relatives. Identification of human remains can be achieved reliably by comparing certain human characteristics recovered from post-mortem (PM) remains with their counterparts collected from presumed missing persons. It must be based on reliable and objective methodology together with technical and scientific expertise (Avon, 2004, Adams et al., 2013).

However, as with the many methods used in human identification, traditional forensic odontology techniques can sometimes face unsuitable situations such as lack of ante-mortem (AM) dental records and when information from available dental records is insufficient for identification purposes. Hence, the availability of good quality, contemporaneous and clear records are essential in forensic dental identification. Unfortunately, this is not always the case and the maintenance of dental records varies considerably between countries. For instance, in a developing country like India, most of the dentists do not maintain proper dental records or the completeness and quality of the records is inadequate for identification purposes. Recent studies (Astekar et al., 2011, Preethi et al., 2011, Sarode et al., 2017) assessed the awareness of the importance of dental record maintenance among dentists. It was found that a very low percentage (12 - 38 %) of the dentists maintained dental records, and there was inadequate knowledge of the usefulness of dental records in forensic cases.

Studies from various countries such as Indonesia, Thailand, Sri Lanka, Pakistan, Saudi Arabia, Libya, Sudan, South Africa, Poland and the United Kingdom also reported the lack of completeness and accuracy in routinely recorded dental records (Zikir and Mânica, 2019, Prayoonwong et al., 2019, Gooneratne, 2015, Akram et al., 2019, Meisha, 2019, Ali et al., 2017, Waleed et al., 2015, Mthethwa and Matjila, 2019, Lorkiewicz-

Muszyńska et al., 2013, Brown et al., 2017). In such circumstances it may be useful to examine photographs available from the family, relatives or friends of a deceased person. The justification was based on the shape, dimensions and alignment of the teeth of an individual, which can comprise a specific and unique set. (McKenna, 1986). Furthermore, photographic identification has become important with the increasing number of cases (illegal immigrants) with no AM dental records (De Angelis et al., 2007). This creates a potential forensic identification opportunity, particularly where the dental records are less than ideal.

There has been a growing trend in the use of digital cameras, where the main focus is centered on the face of the individuals, more specifically on the smile. Therefore, photographs of the smile may constitute a reliable source of AM information with the potential to help solve certain cases of human identification (Silva et al., 2008).

A smart phone is a multifunctional cell phone that provides voice communication, text messaging and imaging capabilities and facilitates data processing as well as enhanced wireless connectivity (Zheng and Ni, 2006). In the modern society, access to smartphones is also widely available. According to a recent survey, in the past five years, about 1.4 billion smartphones were sold worldwide annually (Statista, 2020). With the development of smartphone technology, these advanced hand-held devices have enabled individuals to take photographs or selfies and share them instantly on social networking sites. Furthermore, the use of selfie photographs for identification of a carbonised body by using the smile line and image superimposition was first reported in a case study (Miranda et al., 2016).

With the advent of 3-dimensional (3D) technology opportunities have arisen for reliable and accurate methodologies for forensic studies using 3D laser scanners. The dental casts can be fabricated from the dental impressions and laser scanned to create indirect 3D digital images of dental models using laboratory study model scanner (Thali et al., 2003a, Blackwell et al., 2007, Evans et al., 2010, Sheets et al., 2013, Martin-de-Las-Heras et al., 2014) and intra-oral scanners (Naidu and Freer, 2013, Martin et al., 2015, Chalmers et al., 2016). Various software packages; Geomagic Studio® (GS) (3D Systems®, Rock Hill, SC, USA); Cloud Compare® (CC) (Telecom Paris Tech® and EDF®, Paris, France); and Maestro 3D Ortho Studio® (MS) (AGE Solutions®, Pontedera, PI, Italy), were designed for the morphological comparison of 3D laser scanned anterior dentition models and investigations on the uniqueness of human dentition (Franco et al., 2016).

The application of 3D imaging has not been explored or utilised to its full potential in human dental identification. Moreover, the lack of completeness or accuracy of the routinely recorded dental records, as reported in many countries worldwide may be inadequate for human identification. Alternative methodologies utilising the latest technical and scientific expertise are worth exploring. Hence, the present research was focused on integrating the 3D technology with the 2-dimensional (2D) photographs and selfies' when the AM dental records are not available. Also, a feasible and efficient automated dental identification system using 3D dental models and intra-oral scans from the available AM dental records was explored to enhance the identification process (see Figure 1.1).

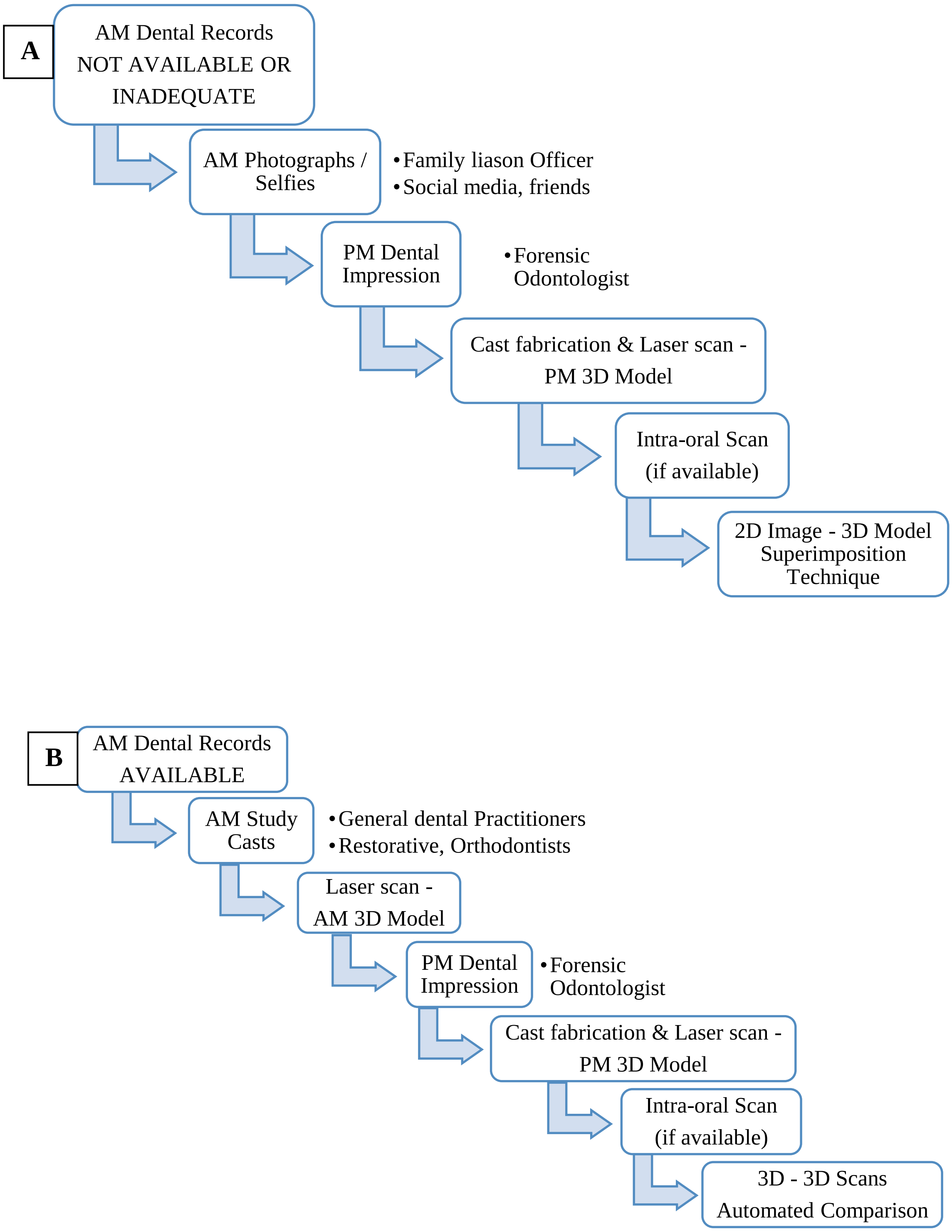


Figure 1.1 Proposed outline of approach - A and B.

1.2 Aim of the Research

To explore the use of digital photographs of smile, selfies and 3D imaging to assist with human dental identification.

1.3 Specific Objectives

1. To increase the accuracy of photographic dental identification by comparing 2D photographs of a smile and selfies with 3D dental scans using a superimposition technique.
2. To develop a new automated dental identification software and compare AM and PM 3D dental scans to test its accuracy and validity.

1.4 Principal Research Questions

1. Can any deceased individual be identified by comparing AM and PM digital photographs and selfies with 3D models ?
2. Whether two identical 3D dental models can be matched digitally using dental features/patterns with an automated software?

1.5 Rationale for the research

This study explores an innovative way to assist the PM human identification using AM photographs of a person smiling, selfies and 3D digital images of dental models and intra-oral scans.

1.6 Hypotheses

The study hypothesis is that a 3D imaging technique could be used to assist with human dental identification. The null hypotheses to be tested are:

1. Superimposition of 2D photographs of a smile with its corresponding 3D dental model is reliable and enables a higher degree of certainty in human identification.
2. Identical 3D dental models/scans can be effectively compared and positively matched using an automated identification software.
3. Selfies can be considered as AM data that could aid in dental identification.

1.7 Ethical Approval

This research protocol has been approved by the East of Scotland Research Ethics Service, REC reference: 17/ES/0144, Integrated Research Application System ID: 236508, Amendment Number: AM01. The Ethical Approval Letter, NHS Tayside Letter of Access for Research and the Amendment approval are attached as Appendices A, B and C respestively.

Chapter 2 - Literature Review

2.1 Forensic Dental Identification

The forensic odontologist assists legal authorities with identification in cases involving a single death, a major incident or a mass disaster. In the United Kingdom, the forensic odontologist usually enters the investigation at the request of police or coroners (England, Wales and Northern Ireland), procurator fiscal in Scotland, often after other identification methods have been unsuccessful (Hinchliffe, 2011, Brown and Sheasby, 2018).

A scientific method of identification is often necessary as the advanced state of decomposition or incineration render visual identification inappropriate and unreliable. Comparative identification is the comparison of two dental records; the PM dental record (the state of the dentition of the unidentified body after death) and the AM dental record (the state of the dentition of a missing individual before death or before the person went missing) (Carabott, 2013).

Before examination, original and complete AM dental records should be obtained by the police (family liaison officers) and ideally be available at the time of the PM examination. Computerised records should be available in full colour. In general, the PM examination and comparative dental identification is performed by two forensic odontologists, one clean and one dirty, each performing the dental examination with the aim to record all relevant information in a single examination and avoid a second examination of the body (Clement and Ranson, 1998, Brown and Sheasby, 2018). Following a full intra-oral examination, the PM and AM composite charts (prepared using Interpol Identification forms - dental pages 600s), radiographs and photographs are examined for points of comparability / incomparability. When AM records are not available at PM, it is recommended to take full mouth radiographs. The odontologist must be familiar with, and capable of using, portable x-ray machines and suitable photographic equipment. The forensic odontologist should also take photographs when required during the PM examination and consider comparison with AM smiling photographs. One of the following conclusions need to be recommended to the Coroner / Procurator Fiscal at the earliest opportunity (Brown and Sheasby, 2018).

1. Established – Identity is confirmed beyond reasonable doubt.
2. Probable – Identity is strongly suggested.
3. Possible – Identity is suggested.
4. Exclusion – Irreconcilable differences exist.
5. Insufficient information to enable a comparison.

A complete and contemporaneous report represents good practice in human identification by dental means. A full report provides a robust and defendable record of the evidence available, the process of examination, composite PM and AM charts, explanation of any discrepancies and the conclusions reached. The original AM dental records should be returned to the instructing authority on completion and submission of the odontology report. It is also recommended that any materials pertaining to the PM examination, such as documents, radiographs, photographs and evidence be stored appropriately and securely, and ideally indefinitely but not for less than a minimum of seven years (Tucker, 2014, Brown and Sheasby, 2018).

Forensic odontologists may also be involved in disaster victim identification (DVI). This process is similar to a single case identification, but multiple bodies or body parts are involved and comparison of AM and PM dental profiles aim to establish the identity of multiple persons. DVI can be complex and requires the skills and expertise of fully trained and experienced forensic odontologists, sometimes working in large teams (Hill et al., 2011).

The Centre for Research on the Epidemiology of Disasters defines a disaster as “a situation or event which overwhelms local capacity, necessitating a request to a national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction and human suffering”. For a disaster to be entered into the database, at least one of the following criteria must be fulfilled: 10 or more people reported killed; 100 or more people reported affected; declaration of a state of emergency; or a call for international assistance (Below et al., 2009). It is important to distinguish between open and closed forms of disasters. An open disaster is referred as a major catastrophic event resulting in the deaths of a number of unknown individuals for whom no prior records or descriptive data are available (INTERPOL, 2009), for example the 2004 Boxing Day tsunami in South-East Asia (Schuller-Gotzburg and Suchanek, 2007). In contrast, a closed disaster is defined as a major catastrophic event resulting in the deaths of a number of individuals belonging to a fixed, identifiable group for example an aircraft crash with passenger list (INTERPOL, 2009) and the Grenfell Tower disaster, London 2017 (Rutty et al., 2020). A combination of an open and closed disaster can occur when airplanes crash into residential areas, as in the case of the Lockerbie bombing in 1988 (Pan Am flight 103) (Moody and Busuttil, 1994) or the Concorde crash in 2000 (Air France flight 4590) (Laborier et al., 2004).

The DVI process requires that expertise from different areas (police, medical and dental specialties) are integrated and work towards the common goal of identifying all victims. The UK follows the Interpol DVI guidelines, which recommend cooperation with other national DVI teams when different victim nationalities are to be expected

(Carabott, 2013). The dental identification techniques are dependent on the presence of adequate dental remains, and on the availability and quality of dental records (Forrest, 2019).

2.1.1 Usefulness of Dental records:

Identification using dental records is an efficient, reliable and economical procedure, often used in combination with other means of identification (Sweet, 2010, Senn and Weems, 2013). Good quality dental records are an essential part of patient dental care and are necessary for dental identification. The AM dental records include charts, computerised and written records, radiographs, photographs, laboratory slips, referral letters, study models, working models, orthodontic appliances, mouth guards, occlusal splints and bleaching trays (Hinchliffe, 2011, Brown and Sheasby, 2018) .

The general dental practitioner has a principal role in the PM phases of identification as custodian of the AM patient records. The records must be retained by the practising dentist and then passed on to another custodian of records, for instance a different dentist if the patient chooses to, or the police / coroner in cases needing dental identification. It is also recommended that the dentists maintain copies of the released original records for their own files along with a signed and dated receipt from the collection authority (Silver and Souviron, 2009, Sweet, 2010).

According to the National Health Services Records Management Code of Practice for Health and Social Care in the United Kingdom, the dental practitioners are encouraged to put a maximum period of 11 years on retention of records for adults and to the age of 25 years for minors, whichever is the greater (NHS, 2016). The guidelines on dental records by the Dental Board of Australia under S39 of the Health Practitioner Regulation National Law Act 2009 (the National Law) require retention for at least seven years from the last occasion on which a health service was provided in case of an adult and for an individual who is under the age of 18 years, the records to be retained until an age of 25 years is attained (ADA, 2018). According to the Royal College of Dental Surgeons of Ontario guidelines, dentists are legally required to keep dental records; clinical and financial patient records, as well as radiographs, consultant reports, and drug and laboratory prescriptions must be maintained for at least 10 years after the date of the last entry in the patient’s record. In the case of a minor, these records must be kept for at least 10 years after the day the patient turned 18 (Royal College of Dental Surgeons of Ontario, 2008). While a new Limitation Act was introduced in British Columbia, Canada, effective June 1, 2013 where the dentists must maintain complete patient records for which the most recent entry was created on or after June 1, 2013, must be kept for 16 years from the date of last entry. For minors the records must be retained for 16 years after the day the minor reaches the age of 19 (College of Dental Surgeons of British Colombia, 2013). While in the majority of states in the United States of America, the patient record keeping requirements are specified in their state legislative/regulations. For example, for New York State, all patient records must be retained for at least six years following the last patient visit (NYSED, 2019).

The Indian Dental Association recommends that, for practicability, a doctor may maintain records up to a minimum of 5 years to satisfy consumers and the judiciary, for protection against medical negligence and complications. The Dental Council of India has not formulated any specific regulation or guidelines (Astekar et al., 2011).

Another important factor for lack of dental records or perhaps the access to dental services is due to inequalities in socio-economic status. The low economic or income groups do not use dental services to the same extent as the high income groups and affordability is a major barrier (Bommireddy et al., 2014, Kailembo et al., 2018). Delhi is the fifth largest city of the world and second in India in terms of population. Normally, when an unclaimed body is found, an advertisement is run in newspapers for identification, see Fig. 2.1. A five-year retrospective analysis (for the period 2010–2014) of medico-legal autopsies in the south and south-east districts of Delhi, found that unknown bodies accounted for about 16% of cases (Yadav et al., 2016). The authors called for the creation of a national missing persons database and a DNA database in order to assist with the identification of unidentified, unclaimed and unknown bodies.

Figure 2.1 Public appeal for body identification through newspaper advertisements. Adopted from the Advert Gallery, Times of India, Delhi (TOI, 2017).

Not every country has rigorous standards for the documenting of dental treatment and retention of dental records. Mostly in developing countries, the frequent absence of good dental records may not facilitate dental comparison. The perspective of maintaining a good dental record may vary with the knowledge and awareness of the general dental practitioner. For example, the records might be considered “good” as a record of the treatment provided, but perhaps a full mouth chart may not be deemed necessary as part of the records when considering the knowledge, awareness and forensic importance of quality dental records by dentists from the developing countries.

The dental charting is one of the key components of any dental record, and forms a fundamental part of each dental examination. It is a diagrammatic representation of the patient’s mouth that enables the dentist to visualise the number of teeth, the type and location of any restorations present in the natural dentition, the type and nature of prostheses; fixed (bridges and implants) and removable, along with a detailed treatment plan for the future, at a glance. It may be completed by hand or computerised (Brown et al., 2017).

Forensic odontologists often receive dental records that are poorly documented (Brown, 2015), incomplete, or difficult to understand (Manica, 2014). Errors in dental charting could come about for several reasons. One of the most common errors is the incorrect registration of dental restoration, which may occur during the transcription or through carelessness or inattention (Manica, 2014). A recent audit of dental charts from general dental practice in the UK revealed that 44% were incorrect (Brown et al., 2017).

At a time when the Dental Reference Officers were conducting examinations, accuracy of charting was questioned when they observed that less than half (48%) of general dental practitioners charts were the same as the Dental Reference Officers, and 14% did not have a dental chart at all (Platt and Yewe-Dyer, 1995). One study found that only 70% of records had full tooth charts, and NHS records were significantly worse than private records (Morgan, 2001). Military studies have also identified inaccuracies of dental charting, and raised concerns for forensic dental identification (Alexander, 1970, Alexander, 1991). Forensic odontologists too have reported poor dental records in the UK and abroad (Hill et al., 1988, Borrman et al., 1995, Delattre and Stimson, 1999, van Niekerk and Bernitz, 2003, Petju et al., 2007, Manica, 2014).

Since transition into electronic record keeping by medical and dental practices, a number of studies have examined the quality of record keeping in both systems. Comparisons of computer generated and handwritten records in general dental practice in the UK have found that the computerised records were significantly better in detailing a number of generic criteria such as patient identifiers, medical history, dental charting, periodontal condition, soft tissue examination, treatment provided and treatment plans (Spicer, 2008). Another study in the UK compared handwritten and computer entry records for compliance with a number of legal requirements and desirable characteristics for dental records. The authors concluded that computer generated notes achieved a much higher compliance rate with the set parameters, making defence in cases of litigation, continuity of care and clinical audit easier and more efficient (McAndrew et al., 2012).

There are numerous software packages available in the field of dentistry that are designed to assist writing treatment notes, facilitate pictorial charting of dental examination findings on an odontogram, generation of treatment plans, storage of radiographic and photographic images, and features relating to patient management. These software programmes have proforma checklists against which a dentist can be guided through the necessary steps to fulfil the minimum requirements of dental record keeping (Brown, 2015).

Dental identifications have played a key role in natural and man-made disaster situations (Pretty and Sweet, 2001) and the disasters have also demonstrated the importance of dental records for use in forensic dental identification (Soomer et al., 2001, Dumancić et al., 2001, Prajapati et al., 2018). The usefulness of dental records for victim identification following the Indian Ocean tsunami disaster in Thailand, and to evaluate the dental identification system in Thailand was reported (Petju et al., 2007). Below is a graph that demonstrates the usefulness of dental identification (Figure. 2.1).

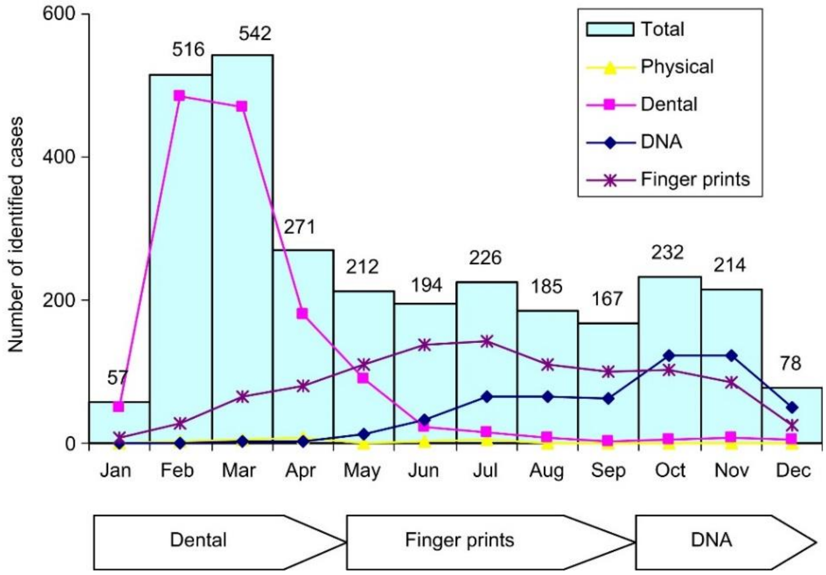


Figure 2.2 Chart depicting the primary identifiers during the first 12 months after the Tsunami in 2004. Adapted from Petju et al., 2007.

The high percentage (more than 90 %) of available dental records assisted the identification of victims from Europe, North America, Oceania and Africa. By December 2005, 3750 bodies had been identified with dental identification contributing to 46.2% of the total as the primary method. Most unidentified missing persons were the victims from

Thailand which was due to a lack of dental records and / or the dental records were inadequate for forensic identification. Only 7.4% of the dental records obtained could be used and 2.0% of Thai victims were identified by this method. In 38.6 % of cases, the method of identification was fingerprints and DNA, which was expensive in cases that required DNA identification. Thus, an alternative and inexpensive method of approach is essential in scenarios where primary methods are ineffective.

With regards to the quality of dental records, a study examined the quality of the AM and PM dental records of the victims of New Zealand used by the DVI team to identify bodies in Phuket, Thailand, following the South Asian tsunami of 2004. The findings underline the usefulness of dental data in human identification, but point to a number of significant sources of error. Of the 78 PM records received, only 68% of radiographs and 49% of photographs confirmed the accompanying dental charting (Kieser et al., 2006).

Disasters in which dental surgeries are destroyed (wildfire, flood, earthquake and tsunami for example) may also impact the availability of dental records (Forrest, 2019). Due to the inability to invest in preparedness or strategies to mitigate a disaster, the numbers of deaths from disasters are likely to occur in countries of low socio-economic status (Cordner and Ellingham, 2017). In such countries, the availability of AM dental records may be limited and / or of questionable quality, and so the contribution that forensic odontology can make will be heavily influenced by these factors. Therefore, when good quality AM records are available, a higher percentage of victim identification using forensic odontology techniques can be achieved. This was demonstrated in the recent Grenfell tower disaster, when dental records were essential in the identification process (BBC, 2017, Independent, 2017).

The value of dental identifications in some high-profile mass casualty incidents in the UK and Tunisia are shown in Table 2.1 (Dr. Phil Marsden, Forensic Odontologist, Dental Identification Manager for UK DVI, Personal Communication, April 2020).

Disaster Type	**City/Country**	**Year**	**Total number of victims**	**Number of victims Identified by Odontology**	**Percentage Identified by Odontology**	**Percentage Identified with AM Dental Records**	**Cases with nil AM Dental Records**
Terrorist Bombings	London	2005	52	40	77%	77%	8
Terrorist Attack (Shooting)	Tunisia	2015	30	30	100%	100%	-
Accident (Tram crash)	Croydon	2016	7	5	71%	100%	2
Terrorist Bombing (Manchester Arena)	Manchester	2017	22	19	86%	100%	3
Terrorist Attack (London Bridge)	London	2017	8	7	87%	100%	1
Accident (Grenfell Tower)	London	2017	70 + 2*	52	74%	74%	18
Accident (Shop explosion)	Leicester	2018	5	4	80%	100%	1**
Accident (Helicopter crash)	Leicester	2018	5	4	80%	100%	1**

*Died off site but did not go through the Westminster Mortuary.

** Social Media Images & PM CT scans.

Table 2.1 The value of dental identifications in mass casualty incidents the UK and Tunisia.

Despite the potential for human error with recording of dental notes and charts, certain elements of the records are considered to be more robust. Radiographs, photographs and study models which capture the dentition reliably at a given point in time. Where these elements of the dental records are available, they may prove invaluable for an odontologist and reduce the need to rely on the dental charts. Radiographs are 2D images, and when available, capture the tooth and root morphology, restorations and surrounding bone trabeculae. Photographs may capture teeth alignment, morphological features such as the shape, position, angulation, size, dental anomalies, discolouration and incisal alignment of the anterior dentition. These photographs may provide valuable information in forensic identification cases and in cases lacking dental records. There may be an opportunity to find them through family, friends or social media networks.

Dental models also capture the teeth alignment, crown morphology, and degree of wear, which can be characteristic features unique to that individual. The availability of study models is advantageous as they can be retained as a 3D physical or digital record of the dentition. Study models permit odontometric analysis both manually and digitally, and allow digital manipulation of the models in any preferred orientation and subjected to quantitative analysis. With the help of a laser scanner, the study models can be transformed into digital models, giving further opportunities for 3D based dental research.

2.1.2 Uniqueness of the Human Dentition

Teeth are the most indestructible components of the human body and may remain intact for many years beyond death. They are biologically stable and contain information about the physiological and pathological events in the life of the individual which remain as markers within the hard tissues of the teeth (Whittaker, 1995). Any therapeutic activity by a dentist in the form of restorations and prostheses may modify an individual's dentition in a unique manner.

The uniqueness of the human dentition is a term used commonly in forensic dentistry, especially in the fields of human identification and bite mark analysis (Senn and Weems, 2013), with the generally accepted view that the human dentition is unique to that individual, except in identical twins (Sheasby, 1998). Human identification relies upon the uniqueness of the human dentition to guarantee that two persons will not present the same dental characteristics, and assures that the identity belongs exclusively to the deceased body (Franco et al., 2016) .

Dental uniqueness is based on the combination of morphological and positional information from all the teeth included in a dentition. In this context, positive matches between different dentitions indicate lack of dental uniqueness. In a forensic scope, the uniqueness of human dentition is commonly used to assess the identity of a person or to link a dentition to a bite mark. In the latter, the number of morphological traits to consider in a search for the uniqueness is much smaller compared to dental identification cases. Indeed, in bite mark analysis, the crown morphology and position of the six-anterior upper and lower teeth is mainly considered (Franco et al., 2015).

The uniqueness of the human dentition is defined by many parameters including number of teeth, restoration type, size of restoration and restoration position. In general, individuals with multiple dental restorations or rare features are easier to identify than those with little or no dental treatment (Pretty and Sweet, 2001). With increasing trends in oral health, the number of patients with incidence of caries decreases and consequently lack restorations (Lagerweij and van Loveren, 2015). This can make the identification process more difficult. As the absence of acquired dental traits can be a problem in some cases, root curvature, bone trabecular patterns, pulpal morphology, pulp stones and supernumerary teeth are now becoming increasingly important for identification purposes (Sweet, 2010).

Uniqueness can only be proven if all parameters are compared between all human dentitions and no matches are detected. Some studies investigated the dental uniqueness in the context of bite marks (Kieser et al., 2007, Blackwell et al., 2007, Bush et al., 2011a, Bush et al., 2011b, Sheets et al., 2011). Their findings are discussed below.

New technological facilities and techniques, such as 3D optical laser scanners, surface scanners, intra-oral cameras, and photogrammetry, have facilitated studies by examining 3D scanned dentitions (Sheets et al., 2013, Franco et al., 2016). These modalities were used in particular for the analysis of the dentition of subjects presenting similar dental traits and maxillofacial growth, such as orthodontically treated patients (Franco et al., 2017, Dyke et al., 2018). The observed dentitions are matched to each other, aiming to investigate a similarity level, indicating whether or not the human dentition is indeed unique for every person. Randomised matching of dental features is one of the most used pathways for the assessment of the similarity between dentitions (Bush et al., 2011a).

Further to the 3D scanned dentitions, computed tomography (CT) techniques enable registration of digital 3D information of all the teeth available in an investigated individual, adding data of the tooth root(s), pulp, enamel, dentine, and cementum. The authors recommend that digital 3D reconstructions of CT images should be studied in order to investigate all possible parameters related to uniqueness (Franco et al., 2013) .

A few studies have claimed to have proven the uniqueness of the human dentition. The study on adult male monozygotic twins, conducted by examining the dental arch form and individual tooth positions using a 2D computer-assisted superimposition methodology revealed that the twins were not dentally identical (Sognnaes et al., 1982). One study (Rawson et al., 1984) claimed uniqueness of the human dentition based on the assumption that tooth position is linearly and uniformly distributed within the human dentition. Bush et al. (2011b) reproduced the study by Rawson et al. (1984) and revealed a non-uniform distribution of tooth position within the human dentition and concluded that inferences about the uniqueness of the human dentition with relevance for bite mark analysis are not supported in an open population. Another study by Bush et al., (2011a) aimed to determine the match rate in a population of maxillary and mandibular sets of 3D digitally scanned models. The alignment patterns ranged from relatively straight to severely malaligned. The study suggested that there is not enough variation in the alignment pattern to make statements of confidence regarding dental uniqueness with regards to the shape of the six anterior teeth of the maxilla and mandible. However, it was found that the dental match rates decreased when using 3D datasets. Kieser et al. (2007) conducted a systematic study using geometric morphometric techniques, including calibration tests and land marking. A stratified sample of 50 orthodontically treated dentitions of patients aged between 17 and 20 years old was selected. The occlusal surfaces of the anterior teeth (canine to canine) were analysed for variations in size and shape and concluded that the incisal surfaces are unique (Kieser et al., 2007).

Blackwell et al. (2007) presented a technique developed for 3D imaging and quantitative comparison of human dentitions and simulated bite marks. The technique allowed image comparison of a 3D dentition with a 3D bite mark. An algorithm, which estimated the probability of a dentition matching its corresponding bite mark, was developed. The results indicated that 15% of non-matching combinations were indistinguishable from the true match. The authors opined that even with a more varied sample, the possibility still exists that a number of people may have dentitions similar enough to produce indistinguishable bite marks. Sheets et al., (2011) aimed to compare the match rates between orthodontically treated and non-treated dentitions. The study was performed using a convenient patient sample of 110 mandibular models. It was observed that orthodontic treatment had a very strong effect on dental shape similarity. The match rate in the known orthodontically treated sample was 42.7%, which is according to the authors, a confirmation that when orthodontically treated or naturally well-aligned, dentitions may be indistinguishable. The authors also opined that the orthodontically treated human dentition is not unique, when measured with high accuracy and precision.

Recently, the assumption of uniqueness for any particular forensic feature has come under scrutiny from several sources, the most prominent being the 2009 National Academy of Sciences report (Council, 2009), which concluded that in most forensic science disciplines, no studies have been conducted of large populations to establish the uniqueness of bite marks or features.

Future research should focus on overcoming the limitations found in the past studies. Since the contribution of 3D technology is significantly increasing in the areas of comparative human identification process, 3D pair-wise comparisons between AM and PM dental casts / scans may be performed to identify or exclude an individual on the basis of uniqueness in forensic human dental identification.

2.2 Forensic Dental Photography

One of the most important applied protocols of forensic dentistry is photography. Accurate photography is crucial to forensic investigation as a means of documenting evidence. The requirements for successful pattern injury documentation in forensic photography are time, patience, and preparation (Wright and Golden, 1997). The primary purpose is to photograph evidence before it has changed or been disturbed by third parties (Bowers, 2010).

The collection, preservation, and true reproduction of visible evidence are paramount in identification of bite mark and abuse cases. Photography archives detailed information objectively (Bernstein and Wright, 2018). The investigating dentist requires photographs of a person's dentition for comparison with the written record and any study models made. In a forensic odontology context, the main reason for acquiring an individual's dentition is to make a visual record of the dentition: of a suspect in a bite mark investigation; of a victim for identification purposes and for an age estimation investigation (Evans, 2014).

During the PM examination, the British Association for Forensic Odontology (BAFO) guidelines recommends to photograph the facial structures with antero-posterior and both lateral views. The lip retraction with a further antero-posterior view will enable comparison with AM smiling photographs. Every photograph taken should also include the unique reference number, the time and date. If mandibular disarticulation is being considered, then permission from the Coroner/Procurator Fiscal and pathologist must be sought and granted prior to making incisions (Brown and Sheasby, 2018). Photographs should be taken before any soft tissue is incised, soft tissue flaps raised or jaws resected. These photographs will record the gross findings, including the extent of decomposition and/or trauma to the soft tissues and jaws before commencement of the examination. Once the teeth are cleaned and isolated, photographs of the frontal, buccal and occlusal views should be taken, along with the close-ups of specific fillings or dental anatomy that may be unusual or unique and hence assist in the identification. If any appliances have been recovered with the body, such as dentures, photographs should be taken, with and without such dentures in situ as well as photographs of the appliance outside the mouth with a scale (Carabott, 2013).

In some cases the forensic odontologist may need to rely on any AM photographs that are thought to be of the deceased person for comparison. In such circumstances, the investigator needs to take multiple photographs of the victims head in various positions which create a series of photographs that approximate to the angle of the face in the AM photograph. The 2D superimposition of AM and PM photographs may be applied (Evans, 2014). AM photographs of a smile may be of great value in comparing PM dental findings, such as discoloration, missing and malformed or misaligned anterior teeth (Adams, 2013).

In bite mark cases, photographs provide orientation views and working images upon which analysis and opinions are based. A forensic odontologist should also have some basic knowledge of lens function, and photography guidelines for evidence collection to produce optimal forensic photographs (Bernstein and Wright, 2018). A fundamental component in the process of photographing a bite mark – or any patterned injury – is the correct positioning of the camera to the injury. The professional groups that may record bite mark injuries for further analysis by forensic odontologists in the UK are: police forensic photographers and clinical photographers (mostly well trained); crime scene investigators, forensic odontologists, pathologists and clinicians (paediatricians in forensic cases) (less trained and experienced) (Evans, 2014).

Forensic photography requires consistently accurate results when depicting an object in its 2D representation. A well trained and experienced professional may still produce a certain amount of photographic distortion. Good quality equipment is very important in in achieving the desired result. High-end digital single lens reflex cameras are routinely used and are equipped with a range of lenses and separate flash systems which limit photographic distortion. A 90-degree angle is needed for limitation of angular distortion (Evans, 2014).

The BAFO Guidelines for Good Practice in Bite Mark Investigation and Analysis states that it is good practice, where possible, to photograph bite marks in the presence of a forensic odontologist (Sheasby et al., 2010). Forensic photography depends on an understanding and knowledge of the distortion which occurs in bite marks. Bite mark photographs constitute evidence which is subject to the legal rules governing the admissibility of evidence in the court of law. In the UK, the admissibility depends on proof of continuity of evidence recording, with the well trained police photographing the bite marks thereby ensuring its acceptance by the court (Sheasby, 2013).

The forensic analysis of bite marks in human skin is limited by the distortion of the representation of the biter’s dentition. Primary distortion may occur at the time of biting and secondary distortion may occur subsequent to a bite mark being made or be introduced when a mark is examined or recorded (Sheasby and MacDonald, 2001).

- The two main components of primary distortion are dynamic distortion due to the dynamics of the biting process and tissue distortion due to the nature of skin. Dynamic and tissue distortion are complex and unpredictable phenomena that are closely related because of their simultaneous occurrence during the episode of contact between the dentition and skin.

- The three categories of secondary distortion are time-related, posture and photographic. Time-related distortion occurs when a bite mark changes in appearance with the time elapsed subsequent to the bite being made. Posture distortion and photographic distortion occur during the examination and evidence recording of a bite mark.

A bite mark may demonstrate more than one type of distortion; indeed, some degree of distortion is probably present in all bite marks in skin. The recognition and management of posture distortion and photographic distortion during evidence recording is the responsibility of the examining forensic odontologist. This involves determining the body position, locating and holding the rigid right-angled scale and supervising the photographer (Sheasby, 1998).

The main types of photographic distortion which are prevalent in photographing patterned injuries are: (Johansen and Bowers, 2000).

a. Type 1 distortion, also called angular distortion occurs due to incorrect positioning of a scale. The camera must be perpendicular to the plane of the injury.
b. Type 2 distortion occurs if the scale is not on the same plane as the injury.
c. Types 3 and 4 distortion occurs due to applying too much pressure when the scale is placed next to the injury that warp a portion of the scale, and when the scale is tilted.

The American Board of Forensic Odontology (ABFO) Bite Mark guidelines Committee recommends the use of ABFO No. 2 scale during bite mark photography. It is a rigid, right-angled scale developed by a photogrammetrist and a forensic odontologist for the purpose of minimising photographic distortion and ensuring accuracy in measurements (Wright and Golden, 1997). A standard operating protocol and methodology should be followed by the forensic photographer to ensure complete photographic documentation of the case. The protocol involves careful and complete cataloguing of all images taken, the camera settings and equipment used during the procedure. The orientation images depicting the location of the evidence are made. The photographs are progressively taken closer to the subject until final macro images are obtained. The close-up photographs should be taken with and without the scale. The photographic scale is used for size reference and close-up (macro) images without a scale permit the entire area of interest (patterned injury) to be seen without any obstruction (Bernstein and Wright, 2018). Evans et al. (2012) have reported that if a wound or a feature on the body is photographed at more than a 15-degree angle to the perpendicular, then there will be visible distortion and thus change the pattern that is being investigated.

The precision and accuracy of the image capturing device are of vital forensic importance. The developments in modern dental photography have continued to facilitate and enhance the practice of forensic dentistry. An awareness of all the possible errors in extra- and intra-oral clinical photography will increase the chances of obtaining high quality images.

2.3 Two-Dimensional Imaging

The 2D imaging mainly constitutes photographs and radiographs. A brief review of digital photography and radiographs is discussed in this section.

Photographs have been used in forensic identifications since the 1930s. One of the earliest use of photographic superimposition was pioneered and successfully applied in The Buck Ruxton "Jigsaw Murders" case in 1935. This was the key evidence that led to Dr. Ruxton's conviction and execution for the murder of his wife Isabella and her maid Mary Rogerson. Photographic reconstruction was an important tool in the investigation. The skulls of the two victims were compared with multiple existing portraits to confirm the identifications. Investigators photographed the skull no. 2 in the same orientation as an existing photograph of Mrs. Ruxton. The outlines of skull no. 2 was superimposed on the outlines of Mrs. Ruxton's portrait where the facial outlines seem to correspond (NLM, 2006).

Another case was reported in South Africa in 1950s, where photographic superimposition was accepted as a part of evidence for identification (Prinsloo, 1953). Later, a positive identification based on craniofacial superimposition (CFS) was accepted in an Indian court in 1962 (Sen, 1962).

The evolution of digital technology led to the development and production of digital cameras making a shift from film to digital photography.

2.3.1 Digital Photography in dentistry

Digital photography is described as the images that are stored in a computerised file format referred to as a digital image file. It signifies a file format that is composed of a graphical image instead of text or programme data. These images can be recorded in the form of bitmapped image (JPEG, PNG, GIF, TIFF and BMP) and vector-based images used in paint or illustration programmes (Curtin, 2007).

Photographs are an essential part of the clinical records along with radiographs and study casts. Broadly divided into extra-oral and intra-oral photographs, which can be used for documentation, treatment planning, communication with patients, dental technicians and specialists (Ahmad, 2009a). The digital single lens reflex (DSLR) camera with a high quality (35 mm) lens and a ring flash is considered the ideal choice for dental photography, as it is capable of taking portraits as well as close up or macro images of the dentition (Ahmad, 2009b).

Developments in digital photographic technology have facilitated the integration of photography into clinical dentistry as many practitioners have access to a computer. A study on the use of photography in clinical dentistry in the UK was conducted through a questionnaire. It was found that the private and specialist practitioners were more likely than practitioners in mixed NHS/private practice to use clinical photography. NHS practitioners were the least likely to use clinical photography (Morse et al., 2010).

Clinical photographs are taken before, during and after orthodontic treatment and if captured with a correct camera and orientation, record more useful information about the malocclusion and treatment than any other clinical record. Correct positioning of both the patient and the clinician is required, in a standardised manner, to produce consistent photographs (McKeown et al., 2005). In the modern era, the ability to capture, store, and transmit digital images almost instantaneously revolutionised communication and led to a dramatic increase in the use of electronic media in clinical care and education. As a result, students, educators, and clinicians have become accustomed to viewing high quality images and videos. Consequently, demand has increased for medical and dental images (Stieber et al., 2015).

Digital photography can transform the quality of clinical record keeping and capture details that would be difficult or impossible to record in any other way. The ‘gold’ standard series of photographs required by the American and British Academies of Cosmetic Dentistry are a good basis for recording the dentition (Wander, 2014).

2.3.2 Radiography

2D conventional radiographs provide excellent images for most dental radiographic needs, with a primary use to supplement the clinical examination. When AM radiographs are available, it is a vital forensic investigative procedure and is advantageous over photographic evaluation as external and internal anatomical features can be analysed. Radiographs capture the unique morphological features of teeth, root curvatures, restorations, endodontic treatments, surrounding structures and physical detail of dental treatment and any changes to the dentition of an individual.

Comparison of AM and PM dental radiographs are accepted as one of the most reliable and effective identification procedures used for single cases or for mass disasters (Wood and Kogon, 2010). Achieving PM reproduction of an AM radiograph in terms of radiographic angulation provides a strong case for expressing an opinion in confirming the identity (Forrest and Wu, 2010). The advantage of comparing patterns and shapes of fillings and anatomical features other than just location and presence of fillings and teeth is immense and can change a possible identification to an established one (Carabott, 2013). Where there are no AM radiographs but records indicate that pins, implants or root fillings are present, it may be appropriate to take PM radiographs to confirm their presence. When AM records are not available it may be appropriate to take full mouth radiographs (periapicals, left and right bitewings) and occlusal views for impacted teeth. The radiographs should be checked for quality prior to further examination (Brown and Sheasby, 2018).

Radiographs play an important role in the estimation of age from the dentition of children and adults. Radiographic analysis of the developing dentition as well as the clinical tooth emergence in various phases will help in age determination. Demirjian's method (1978) is the most widely used for scoring the stages of tooth development (AlQahtani, 2014). Kvaal et al. (1995) developed a method for estimating the chronological age of an adult from measurements of the size of the pulp observed on periapical radiographs from six types of teeth; a regression analysis formula was used, with age as the dependent variable and gender as an independent variable. Orthopantomographs were used in developing a method for assessing chronological age in children based on the relationship between age and the measurement of the open apices in teeth (Cameriere et al., 2006). Later, the orthopantomographs were used to examine the relationship between age and age-related changes in the pulp/tooth area ratio in monoradicular teeth (Cameriere et al., 2012).

Digital radiography has become an integral part of dentistry due to reduced X-ray doses, and instant generation of images. Portable X-ray devices are developed to facilitate radiological imaging in dental practices and also forensic settings. A Nomad® is a hand-held X-ray device combined with a digital sensor and a portable computer used in forensic odontology applications. It was first employed in a forensic dental setting during the 2004 tsunami victims identification, and has now been approved for use in the dental setting (Danforth et al., 2009, Carabott, 2013).

2.4 Three-Dimensional Imaging

3D imaging has evolved greatly in the last three decades. In medical imaging, a 3D image is a time sequence of radiographic images or tomographic slice images of a dynamic object, a volume of tomographic slice images of a static object. Digital imaging methods such as ultrasonic evaluation, X-ray Computed Tomography (CT), positron emission tomography - CT (PET-CT) and Magnetic Resonance Imaging (MRI) are widely used in the medical and dental disciplines. These methods are capable of producing sets of 2D images and 3D reconstructions for interpretation. (Udupa and Herman, 1999).

3D images derived from X-Rays, scans or digital Cone Beam Computed Tomography (CBCT) are components of supplementary diagnostic procedures. These procedures assist the practitioners in visualising the anatomical relationships of internal organs or teeth for diagnostic and treatment purposes (Blatz and Conejo, 2019).

Using the X-ray-based CT imaging technique, 3D data of the mineralised tissues can be reliably obtained. The CT methods were originally developed in the early 1970s as a medical imaging technique by Houndsfield, which are invariably associated with varying degrees of ionising radiation (Hounsfield, 1973). In contrast to CT, MRI provides excellent soft tissue analysis. This technique is based on the principle of nuclear magnetic resonance with a major advantage for human diagnostics due to the absence of any form of ionising radiation (Cammoun et al., 1985).

2.4.1 Concept of 3D imaging

The Cartesian coordinates system is used in 3D medical imaging, which specifies each point uniquely in a plane by a set of numerical coordinates. The 3D images consist of the x-axis (or the transverse dimension), y-axis (or the vertical dimension), and the z-axis (the antero-posterior dimension 'depth axis'). The x -, y - and z - coordinates define a space in which multi-dimensional data are represented and this space is called the 3D space (Udupa and Herman, 1999).

The generation of 3D models occurs in a stepwise manner. The first step, 'Modelling', uses mathematics to describe the physical properties of an object. The modelled object can be seen as a 'wireframe' (or a 'polygonal mesh'). The mesh is usually made up of triangles or polygons and it is used as a mode of visualisation. During the modelling procedure, a layer of pixels are added to the surface of the object and this is called 'image' or 'texture mapping'. The second step is to make the 3D object more realistic. The final step is called 'rendering', in which the computer converts the anatomical data collected using diagnostic imaging equipment, processed by a computer and then displayed on a 2D monitor to give the illusion of depth. Depth perception causes the image to appear in 3D (Seeram, 1997).

2.4.2 Application of 3D imaging in dentistry

3D imaging has evolved into a discipline of its own, dealing with various forms of visualisation, manipulation and analysis of multi-dimensional medical structures and has found applications in orthodontics, as well as in oral and maxillofacial surgery (Hajeer et al., 2004). Furthermore, 3D imaging data can be used to generate medical models or surgical templates, which can be used for education, preoperative planning, surgical simulation, and intraoperative guidance (McDonald et al., 2001). With technological advances, a number of 3D imaging methods such as CBCT, stereophotogrammetry, laser scanning and intra-oral scanning have been developed.

2.4.2.1 Cone Beam Computerised Tomography

CBCT scanners were pioneered in the late 1990s for the oral and maxillofacial region. (Mozzo et al., 1998, Arai et al., 1999). The possibility of visualising any aspect of the dental and craniofacial structures in 3D together with a low radiation dose increased interest in this new imaging technique in dentistry (Hatcher and Aboudara, 2004). It is becoming widely available and has applications in orthodontics, implant dentistry, endodontics and oral surgery.

The resolution is measured in voxels instead of pixels, which is often sharper than a conventional CT. The scans are stored in the DICOM format (digital imaging and communications in medicine) and can be converted into a 3D graphical format which allows navigation of various orthogonal slices (axial, sagittal and coronal) through image segmentation (Cevidanes et al., 2006). However, it would not be particularly suitable for examining lesions involving both soft tissues and bone, unless only the bony element is being investigated (Dawood et al., 2009).

Superimposition of CBCT images were performed for 3D evaluation of a patient's craniofacial growth or for comparing craniofacial structures before and after treatment (Cevidanes et al., 2005, Da Motta et al., 2010). The most commonly used techniques for CBCT scans' superimposition are landmark-based, surface-based and voxel-based. A study was conducted to evaluate the accuracy and reliability of these techniques and concluded that surface-based and voxel-based superimposition methods using the anterior cranial base as a reference structure were accurate and reliable in detecting changes in landmark positions when superimposing. While landmark-based superimposition method was reliable but less accurate than the other methods (Ghoneima et al., 2017).

Studies have proposed techniques that integrated the maxillofacial CT bone model with the digital dental models obtained using a laser scanner (Kim et al., 2010, Park et al., 2012, Lin et al., 2013, Lin et al., 2015) and intra-oral scans (de Waard et al., 2016), enabling simultaneous 3D representation of the skeletal structure, teeth, and occlusions. CBCT technology has been used to create 3D images of the dentition by direct scanning of dental impressions, study models and the patient. A study compared the measurements taken from study models, direct intra-oral scans and CBCT scans of impressions and found that these methods were reliable to obtain dental measurements for diagnostic purposes (Wiranto et al., 2013).

CBCT imaging should only be considered if the additional information provided by the reconstructed 3D images would aid diagnosis and or enhance the treatment plan (Abella et al., 2015).

2.4.2.2 Stereophotogrammetry

The terminology for this technology is derived from the terms photogrammetry, which is the science of making reliable measurements from photographs, and stereo, which refers to the use of two or more cameras configured for simultaneous image capture to create 3D coordinates (Slama, 1980). The 3D stereophotogrammetry system uses data from multiple digital cameras that simultaneously capture an image of the same object from different angles. The image is calculated from a collection of points obtained along an x, y, and z coordinate system. The introduction of 3D stereophotogrammetry creates a practical method for objectively comparing surgical results (Mailey et al., 2015).

The earliest clinical use of stereophotogrammetry was reported in 1944 who recorded change in facial morphology produced by orthodontic treatment (Burke and Beard, 1967). Due to fast capture speeds and ease of use, 3D digital stereophotogrammetry is quickly becoming the preferred facial surface imaging modality. Acquiring consistent high quality 3D facial captures requires planning and knowledge of the limitations of these devices. The most common 3D surface imaging system is based on digital stereophotogrammetric technology. These systems are capable of accurately reproducing the surface geometry of the face, and map realistic colour and texture data onto the geometric shape resulting in a lifelike rendering (Heike et al., 2010).

A photo-realistic model by registering 3D facial images acquired with a laser scanner and 3D spiral CT images was developed (De Groeve et al., 2001). 3D photographs and the 3D bone images derived from CBCT can be merged to produce a virtual craniofacial patient with natural surface texture (Jayaratne et al., 2012).

A few studies have evaluated the feasibility of integrating 3D photographs and CBCT images (Khambay et al., 2002, Ayoub et al., 2007, Maal et al., 2008, Jayaratne et al., 2012); and on the accuracy of their registration and superimposition (Naudi et al., 2013). A technique to combine and validate stereophotogrammetric images of the face using CBCT data and a digital dental model was attempted (Codari et al., 2016). Integration of digital dental casts and 3D facial photographs was also proposed (Rangel et al., 2008). As the anterior teeth are used as the reference, any displacement or inclination of the digital dental arch would add a position error in the posterior region. A technical evaluation on this integration found a reliable reproduction of dentofacial relationships with marginal error (Rosati et al., 2010).

This 3D photogrammetry system can assess the coordinates of facial landmarks with good precision and reproducibility (de Menezes et al., 2010, Ceinos et al., 2016) and was found to be the preferred method for rating facial characteristics (Zhu et al., 2017). Photogrammetric 3D reconstruction system was found to generate 3D models of dental arches, reproduce their occlusion, and to perform a set of standard measurements in automated mode (Knyaz and Gaboutchian, 2016). Stereophotogrammetry may be obtained for patients with more complicated conditions such as facial asymmetry or a cleft, and for those with other syndromes (Ueeck et al., 2013), and used for diagnostic and therapeutic purposes. The 3D facial scanning could be a useful and reliable tool to analyse the circumoral region for orthodontic and orthognathic surgical diagnosis and treatment planning (Zogheib et al., 2018).

2.4.2.3 Laser scanning

Computer Aided Design – Computer Aided Manufacturing (CAD-CAM) systems were initially developed in 1950 by the defence arm of the United States Air Force for use in aircraft and automotive manufacturing and the first restoration was milled in 1983 (Blatz and Conejo, 2019). The clinical use of CAD-CAM devices includes diagnosis and treatment planning for implant surgery, prosthetic rehabilitation, and orthodontic treatment to the fabrication of restorations and maxillofacial prostheses. These laser systems can capture 3D images of tooth preparations from which restorations are directly manufactured.

Laser / surface / non-contact optical scanners are devices that create a digital map of the surface of an object and collect data on its 3D size and shape which works on the principle of triangulation. The raw data is usually obtained in the form of a point cloud, representing the 3D coordinates of the digitised surface (Ireland et al., 2008).

Digital scanning can be used in orthodontics for a variety of applications such as treatment planning, indirect bonding tray fabrication, palatal and lingual custom appliance design and construction and clear aligner technology (Martin et al., 2015); the scoring of surgical outcomes in patients with cleft, lip and palate abnormalities (Asquith and McIntyre, 2012). The accuracy of the laser or non-contact surface scanner has been investigated widely (Kuroda et al., 1996, Shah et al., 2004, von Wilmowsky et al., 2015, Bohner et al., 2017).

One limitation of the technique is that the beam of the laser cannot reach undercuts; this can be solved by capturing the study model from several different angles, which enables the production of a 360° model with a very high accuracy (Barry, 2011). Once the 3D model has been produced, it can be saved and exported to a viewing software, most commonly in a stereolithographic (STL) format.

Both the impressions and plaster study models and can undergo laser scanning to create digital study models. The advantage of scanning impressions is that it negates the requirement to pour the study models. The procedure requires the upper and lower study model or impressions to be scanned separately and the occlusion is recorded by articulating the models and scanned. A scan of the bite registration material is required when digitising impressions. Other systems require destructive scanning in which the plaster model needs to be sectioned, and each slice is scanned individually (Torassian et al., 2010).

Once the scan has been taken a software package can be used to create a base for the digital models that simulates bases of trimmed orthodontic study models. Computer packages are available that will allow the digital models to be viewed, measured, analysed and linked to the patient's digital case record (Barry, 2011). Newer systems are currently being developed that are likely to substantially reduce this scanning time and captured with sufficient precision (Ireland et al., 2008).

2.4.2.4 Intra-oral optical Scanning

The latest innovation in CAD/CAM technology towards digital dentistry has been the implementation of optical intra-oral scanners (Naidu and Freer, 2013, Ting-shu and Jian, 2015). The first intra-oral scanner was introduced in late 1980 and was commercially available as CEREC® by Sirona Dental Systems LLC (Charlotte, NC) system for restorative dentistry (Moörmann, 2006).

The computer processes the data points collected from the scanning unit or hand-held wand. The images are merged together to create a complete 3D dental arch, or a map of the intra-oral structures using various non-contact optical technologies and are viewed in real-time on a monitor. These technologies include confocal microscopy, optical coherence tomography, 3D in motion video, triangulation and interferometry (Kravitz et al., 2014).

These chairside devices scan the patient's dentition an as alternative to traditional alginate or polyvinyl siloxane impressions. The development of optical scans has several advantages that include, elimination of the shortcomings associated with traditional, technique sensitive impression taking; rapid access to 3D diagnostic information; easy transfer of digital data for communication with professionals and patients; reduced storage requirement and replace plaster models in orthodontics with no detriment to any resultant clinical information (Fleming et al., 2011, Kravitz et al., 2014, Martin et al., 2015).

Studies have shown that intra-oral scanning was more acceptable in terms of patient perception and comfort over traditional impressions (Yuzbasioglu et al., 2014, Chalmers, 2015, Burzynski et al., 2018). The accuracy and precision of the intra-oral scanners has been investigated using different methods (Ting-Shu and Jian, 2015, von Wilmowsky et al., 2015, Kim et al., 2018); and with different scanner systems, it was concluded that 3M and TRIOS had a higher accuracy than CEREC Omnicam (Nedelcu et al., 2018). The accuracy is enhanced by reducing the span of scanning, and ensuring the scanned surfaces exhibit minimal irregularities (Abduo and Elseyoufi, 2018)..

A recent study described a digital technique that combines intra-oral digital scans with a 3D facial scan to predict the treatment outcome of anterior teeth and provide virtual treatment planning (Park et al., 2019). Direct digital scanners are reliable and with a number of commercially available systems around the world, is likely to become a routine procedure in clinical practices in the future.

2.4.2.5 Digital storage

One of the practical benefits of 3D models and scan is reducing vast physical storage requirements. This has advantages for orthodontic practices as they store initial and final models of their patients. This also helps overcome the drawbacks of the plaster models and reduces the issues with missing and broken models, and transportation, which can be significant for audit and research (Martin et al., 2015).

Archiving study casts in a 3D format is reliable, producing durable images without any fear of loss or damage to the original casts and accommodates large numbers in a small capacity hard disk (Hajeer et al., 2004). Digital models are part of a patient's confidential medical record and dental practitioners must conform to the Data Protection Act (1998). The retention periods are also similar for digital model and plaster model storage (Martin et al., 2015).

2.4.3 Application of 3D imaging in Forensic odontology

Advances in computer and electronic technology resulted in the development of 3D imaging technology and is one of the key components in the rapidly evolving digital dentistry. It is becoming widely available and has applications in the field of forensic odontology.

As discussed earlier, radiological imaging is considered an important aspect of forensic dental identification. The application of CBCT data for identification is as good as using conventional dental radiographs, with the added advantage of the third dimension and the ability to reformat images comparable to the AM conventional radiographs available (Carabott, 2013). 3D image analysis provides superior and more detailed information compared with conventional plain 2D radiography (Anderson et al., 2014). The adoption of a single modality of mobile mass disaster CT was proposed that could replace the current use of multiple radiological sources within a mass fatality mortuary (Rutty et al., 2007).

Post-mortem computed tomography (PMCT) was first reported for a drowning death after a diving accident in 1983 (Krantz and Holtas, 1983). The use of PMCT in DVI increased in the past two decades and has become a reality in the emergency mortuary setting, providing a wealth of information that is relevant not only to the pathological and wider investigation but also for the purpose of identification (Sidler et al., 2007, O’Donnell et al., 2011).

Accuracy of identification using PMCT and AM dental radiographs was comparable to when using PM and AM dental radiographs (Ruder et al., 2016). As a result, there is a potential for dental PMCT to replace conventional PM dental radiographs in the DVI process (Nguyen and Doyle, 2018).

More recently, a case was was reported in which PMCT data acquired as part of the standard mortuary procedure enabled odontological confirmation of identity with the aid of a 3D printed dental model, avoiding the need to resort to disfiguring facial incisions in order to expose the dentition of a charred body (Biggs and Marsden, 2019). The first use of remote radiology reporting for DVI using a mortuary-sited mobile PMCT was successfully employed during the Grenfell Tower disaster. All the victims who died at the scene underwent PMCT imaging and the scans were reported by a multi-professional remote reporting team. They were able to provide 96% of prototype DVI forms, 99% of image datasets and 86% of preliminary reports to the DVI teams in London within one working day of image receipt. (Rutty et al., 2020).

Virtual imaging techniques such as micro-CT and 3D printing have increasingly been adopted to allow detailed analysis and manipulation of anatomical information following medical scanning of remains. Micro-CT was successfully employed to virtually align severed skeletal elements found in different locations, analysed tool marks created during the dismemberment process, and virtually dissect a charred piece of evidence. High resolution 3D printing of the burnt human bone contained within were created for physical visualisation to assist the investigation team (Baier et al., 2017).

Another method of victim identification was attempted by superimposing AM CT data of the head of a suspected individual and PM CT data of an unidentified skull without jaws and were able to establish the identity. The comparison was focused not only on the shapes of the frontal sinuses but also on other anatomical structures of the human skull (Iino et al., 2016). The anatomical uniqueness of the frontal sinuses, both morphological and quantitative, when AM CT scans are available were assessed for its role in the personal identification process (Gibelli et al., 2019a).

The CAD-CAM technology assisted in the application of 3D imaging in bite mark research. Bite mark analysis may offer the opportunity to compare dentitions of suspects to a mark thought to be caused by a bite, based on the individual characteristics of the dentition. A study presented the use of a 3D surface scanner and a new 3D documentation, analysis and visualisation approach based on forensic 3D/CAD supported photogrammetry. This photogrammetric approach and the use of visualisation PM method was claimed to be the first 3D approach for bite mark analysis in an actual case. This method also allows the evaluation of non-protruding injuries such as skin abrasions or intradermal bleeding. The documentation had no distortion artefacts as can be found with standard photography. All the data were documented with a metric 3D measurement, orientation and subsequent analysis in 3D space. It was also highlighted that, beside the metric analysis between bite marks and cast, it is possible to utilise the topographical 3D feature of each individual tooth through their method (Thali et al., 2003a).

A new software package, Dental Print® (2004, University of Granada, Department of Forensic Medicine and Forensic Odontology, Granada, Spain) was developed that generates different comparison overlays from 3D dental cast images depending on the pressure of the bite or the distortion caused by victim-biter interaction. The procedure for generating comparison overlays was entirely automatic, thus avoiding observer bias (Martin-de las Heras et al., 2005).

Biting is a dynamic process, however, many studies have described and quantified bite patterns in two dimensions (photographs, overlays etc.). A technique was developed for 3D imaging and quantitative comparison of human dentitions and simulated bite marks. This technique allows image comparison of a 3D dentition with a 3D bite mark, eliminating distortion due to perspective as experienced in conventional photography (Blackwell et al., 2007). 3D overlays from dental casts were also compared with experimental bite marks by using geometric morphometric analysis (Martin-de-Las-Heras et al., 2014).

Bite marks in food may play an important role in the forensic investigation of a crime. A comparison of bite marks simulated in different kinds of food with the dentitions of the presumed biter was performed. The dental casts of these suspects as well as the bite marks were digitised using 3D surface scanning and were compared in 3D using modelling and analysis software. The scan of each bite mark in food and the comparison were repeated after days, weeks and months in order to investigate the alteration of bite marks in food and the possibility of identifying the biter after the passing of time. The 3D software enabled the act of biting was animated to compare the dentitions with the bite mark (Naether et al., 2012). The use of CBCT in the analysis of bite marks in food stuffs was also proposed. All the used materials were successfully reconstructed as good quality 3D images. The relative densities of the materials in study were compared. The study concluded that CBCT has the potential to become an important tool in the registration and analysis of bite marks cases involving foodstuffs that may be found in a crime scene (Marques et al., 2013).

Research of 2D and 3D methods has shown the apparent limitations of 2D camera capture. When documenting bite marks with standard 2D cameras, errors in photographic technique can occur if best practice is not followed. Subsequent forensic analysis of the mark is problematic when a 3D structure is recorded in a 2D space. A 3D capture is more precise and reduces perspective and angular distortion (Evans et al., 2013).

The methods for age assessment that rely on the development and modification of tooth structures are well known for their validity and accuracy. The pulp-dentinal complex is one of the dental structures that show modifications related to age, mainly resulting in the reduction of the pulp chamber volume due to the continual deposition of secondary dentine. Several studies reported the use of CBCT in investigating the association between chronological age and pulp/tooth volume ratio (Pinchi et al., 2015, Kazmi et al., 2019, Asif et al., 2019).

A newer autopsy technique consists of the internal examination of dead bodies using CT and MRI, without opening the body or body parts. This also allows the reconstruction of a 3D view of the analysed cadaver. This procedure is called “Virtopsy®” (Virtopsy Project®, Zurich, Switzerland) (Pomara et al., 2009).

Access to the oral cavity during the PM photographic and radiological exam becomes challenging with conditions like rigor mortis of the deceased. . In contrast to the classical dental autopsy, the virtual autopsy process allows dental identification in an accurate and quick way, without damaging the body, to access the available dental data (Jackowski et al., 2008). Dental age estimation methods based on tooth development can be applied during the virtual autopsy, allowing the examiner to include or exclude individuals based on age-related victim lists. Through the CT analysis of the Australian bushfire victims, the forensic experts obtained substantial information for human identification based on age estimation techniques. Therefore, the key benefits of virtual autopsy are related to the improved collection of data compared to the traditional technique. The feasibility of visualising 3D anatomical structures thoroughly, in real time, without damaging the body is a remarkable achievement (Franco et al., 2012).

Autopsy facilities across the world are slowly adapting to this change in autopsy practice by placing dedicated CT or MRI scanners into mortuaries but many countries simply do not have the finance, expertise or personnel yet to deliver such a service (Rutty, 2008).

2.4.4 Application of 3D image data in photographic superimposition for human identification

3D images of the face, skull, and dentition can be acquired using different imaging techniques. Stereophotogrammetry and laser scanners, which are non-invasive procedures, acquire images of the face and the dental arches separately.

Craniofacial superimposition (CFS) is one of the approaches in craniofacial identification which involves the superimposition of a skull (or a skull model) on a number of AM images of a missing person and the analysis of their morphological correspondence, the relationship between hard and soft tissues of the face (Stephan, 2009, Wilkinson and Rynn, 2012).

This superimposition has been applied to skulls of unidentified skeletonised remains as a personal identification method. Reconstructed 3D images of skulls from the CT were superimposed with AM photographs of the victim where it was found to be an effective method (Ishii et al., 2011). The manual and computerised superimposition techniques were compared for accuracy and to establish the application of these techniques for disaster victim identification (Wilkinson and Rynn, 2012).

A study was conducted by the integration of a digital dental cast into a 3D facial photograph. For the integration, three digital datasets were constructed: a digital dental cast, a digital 3D photograph of the patient with the teeth visible, and a digital 3D photograph of the patient with the teeth in occlusion. By using a special iterated closest point algorithm, these three datasets were matched to place them in the correct anatomical position. The study concluded the technical possibility to make a dataset of a patient's face with the dentition positioned into this 3D picture (Rangel et al., 2008).

In a case where AM dental records were unsuitable (ambiguous written records and lack of radiographs), a superimposition of the reconstructed PM 3D CT data on a AM Facebook image of the deceased was performed for the purpose of dental identification. It was found that the AM photographs can be superimposed with PM 3D datasets. However, the presence of metallic restorations in teeth may cause artefacts in the image (Wu and Forrest, 2010).

In summary, the future of comparison technologies in forensic odontology may rely on 3D imaging. If optical intra-oral scans become a regular alternative to routine dental impression procedure in the modern dental practice (or even scanning the dentition as part of routine examinations), 3D datasets will increasingly form part of the AM dental profile. Furthermore, CT and possibly CBCT may progressively become more closely integrated into PM examination, and as a result 3D datasets of teeth will become available. Therefore, in years to come, 3D analysis may become a crucial component for the forensic odontologist in a mortuary setting when assisting with human identification.

Chapter 3 - Forensic Dental Identification using Photographs of a Smile: A 2D-3D Superimposition Method

3.1 Introduction:

Traditional forensic odontology techniques for identification are usually unsuitable in cases where the AM dental records of the victim are not available or inadequate for forensic identification. Photographs of the person smiling may provide valuable information. In such cases, teeth can be used in a successful identification process if the AM photographs show visible anterior dentition that is also present in the PM remains for analysis. A positive identification can be achieved by the technique of photographic superimposition (McKenna et al., 1984). The role of the anterior dentition visible in photographs was investigated by enlarging photographs to life-size according to dental measurements (McKenna, 1986). Later, dental superimposition was attempted by studying the occlusal margins of the dentition and highlighted the incidence of special features of each individual dentition. The characteristics for identification visible in a photograph of a smile comprise the shape, position, angulation, size, dental anomalies and incisal alignment of the anterior dentition (McKenna and Fearnhead, 1992).

Smile is one of the most effective means by which people convey their emotions (Hulsey, 1970). The most aesthetic smile is the smile that entirely displays the teeth including some gingiva (Van der Geld et al., 2008). Smiles are broadly classified as the social smile and the enjoyment smile. It is important to differentiate between the social smile and the enjoyment smile. The social smile is a voluntary smile a person uses in social settings or when posing for a photograph. There may be partial / limited teeth exposure due to moderate muscular contraction of the lips. The curve formed by the incisal edges of the maxillary anterior teeth is called as “smile arc” and is seen in the posed smile. The ideal smile arc has the maxillary incisal edge curvature parallel to the curvature of the lower lip. The enjoyment smile is an involuntary / unposed /natural smile and represents the emotion you are experiencing at that moment. The maximal contraction of the upper lips elevator and lower lip depressor muscles causes full expansion of the lips, with maximum anterior tooth and gingival display (Ackerman et al., 1998). The upper and lower lips frame the display zone which is composed of the following smile characteristics: size, shape, position and colour of the displayed teeth, the gingival contour, the buccal corridor, and the framing of the lips (Ackerman and Ackerman, 2002).

Phillips (1999) classified the smile according to teeth and gingiva displayed during a smile into five types:

Type 1 – Display of maxillary teeth only

Type 2 – Display of maxillary teeth and over 3 mm gingiva

Type 3 – Display of mandibular teeth only

Type 4 – Display of maxillary and mandibular teeth

Type 5 – Neither maxillary nor mandibular teeth display

Smiles were further classified according to the four stages in the smile cycle (Phillips, 1999).

Stage I - Lips closed

Stage II - Resting display

Stage III - Natural smile (three-quarters)

Stage IV - Expanded smile (full)

The visibility of the anterior teeth and the gingiva depends on the position of the smile line, which is defined as the relationship between the upper lip and the visibility of gingival tissues and teeth. It is an imaginary line following the lower margin of the upper lip and appears to be convex. Smile was also classified according to the position of the smile line (Tjan and Miller, 1984).

a. High smile: A lip line height that showed the total cervico-incisal length of a tooth and a continuous band of gingiva (minimum, 1 mm) was classified as a high smile line.
b. Average smile: A lip line height that showed 75-100% of the tooth and less than 1 mm of gingival display was visually classified as called as average smile.
c. Low smile: In this type of smile, the lip line height showed less than 75% of the tooth.
d. Gummy smile: A lip line height that showed more than 4 mm of gingiva was classified as a gummy smile line.

The position of the smile line was evaluated on the basis of standardised photographic images in three different ethnic groups: Germanic Caucasian, Roman Caucasian and Asian (Singhalese). It was found that younger females (< 35 years) presented with higher smile lines than older males (> 35 years), a fact which was found in all ethnic groups, while the older Caucasian (Germanic and Roman) and Asian males presented with low smile lines (Jensen et al., 1999).

Another study analysed lip line heights and age effects in an adult male population during spontaneous smiling, speech, and tooth display in the natural rest position. Maxillary lip line heights during spontaneous smiling were generally higher in the premolar area than at the anterior teeth. Smile line heights displaying more than 4 mm of gingiva were perceived as less attractive. In older participants, the maxillary were lip line heights reduced by approximately 2 mm (Van der Geld et al., 2008).

Orthodontics is one of the specialities in dentistry that deals with extensive clinical documentation of the dental elements that determine the smile of individuals. The orthodontic records for most patients include digital or analogue photographs to create pre-treatment records, to assist with planning treatment, for monitoring the progress of treatment and to record post-treatment outcomes (Sandler and Murray, 2001).

In comparison with other AM data, intra-oral photographs have the advantage of registering morphological, therapeutic and pathological identifiers used for dental human identification without exposing the patient to radiation and the need for expensive imaging devices and facilities (Silva et al., 2011). In some situations, smile photographs with an open mouth may also record other identifiers, such as dental restorations and prosthetic appliances (Silva et al., 2015a, Silva et al., 2017).

A case of human identification established on the analysis of intra-oral photographs was reported. The photographs were provided by the relatives of the victim and the same distinctive dental traits were observed leading to a positive identification without explainable discrepancies. The authors recommended the use of intra-oral photographs for forensic purposes due to their practical application, low cost, absence of radiation and reliable tools in the human identification process (Silva et al., 2017)

Few case reports have been published on the use of photographs of a smile in positive human dental identification (Silva et al., 2008, Silva et al., 2015a, Cardoza and Wood, 2015). The AM photograph enabled the application of direct comparison of morphological traits, dental superimposition and the analysis of the incisal contours of the anterior teeth. The AM and PM images were compared, placing the same anatomical region side by side. Using this method, it is essential for the PM image to reproduce the same orientation observed in the AM image. This technique allows the comparison of presence / absence of teeth, the analysis of dental crown morphology, position of the dental arches, presence of dental interventions, and even oral pathologies. A second technique of superimposition requires an imaging editing software such as the Adobe Photoshop. PM photographs in frontal view were selected, cropped and superimposed upon the AM photographs (Silva et al., 2015b). A third technique aimed to highlight the upper and lower incisal edges, using the same image editing software. Thus, the contours of the AM and PM incisal surfaces from canine to canine were detected. Once highlighted, the incisal contours were compared. A positive identification may be possible through the application of these techniques (Silva et al., 2015b).

Dental identification using photographic superimposition became important with the increasing number of illegal immigrants with no dental records (De Angelis et al., 2007). In such circumstances, photographs available from family members, through social networks or friends may provide a significant opportunity for analysis. Advances in digital technology and software have greatly improved the interpretation techniques for imaging photographic data. Studies have developed dental superimposition techniques in 2D using Adobe Photoshop® for enhanced comparative dental analysis of AM and PM photographs. One such study (De Angelis et al., 2007) presented a protocol for evaluating dental superimposition. Adobe Photoshop software was used to make a matrix of the six maxillary anterior teeth. This matrix was then superimposed on the image in question. A theoretical grading scale was developed where a score from 0 to 2 was attributed to each tooth with following criteria: 0 for non-valuable portion, 1 for compatibility and 2 for full correspondence. A non-mathematical scoring system was applied to calculate the index of correspondence as a step towards a quick semi-quantitative method of identifying individuals when other identification methods were not applicable.

Another study (Bollinger et al., 2009) described a method to compare specific criteria-created images of the anterior teeth. In this, an AM photograph layer was created with the software and was superimposed on the PM photograph. Both maxillary and mandibular arches were analysed. The results showed that the chance of reaching a conclusion that leads to identification was increased when multiple individual characteristics were visible in the AM image.

Some studies have investigated the uniqueness of the upper and lower anterior dentition in the general population (Bush et al., 2011b), while in the dentitions of orthodontically treated patients (Kieser et al., 2007, Sheets et al., 2011), it was found that there are significant similarities in human dentition.

3D imaging has evolved greatly in the last two decades. With the advent of 3D technology; 3D optical laser scanners, surface scanners and intra-oral scanners, opportunities have arisen for reliable and accurate methodologies for forensic studies (Sheets et al., 2013). When considering photographic evidence, if the image quality permits comparison, a dental superimposition can be performed between a 3D model of a given dental cast and the 2D image. The teeth visible in an image of a person smiling can be compared and superimposed upon the remains' teeth that need to be identified (De Angelis et al., 2007).

Few studies (Blackwell et al., 2007, Sheets et al., 2013) have reported the free manipulation of 3D digital dental casts on different axes as an advantage, compared to a 2D image analysis and have also highlighted the realistic 3D perspective. While others

(Tuceryan et al., 2011, Martin-de-Las-Heras et al., 2014) worked on the possibility of accurately extracting digital 3D dental contours using specific software and algorithms. The current technology allows for the digital 3D registration, duplication, manipulation, and optimal analysis of human dentitions.

There are no reported studies that have investigated the reliability of a superimposition technique using 2D photographs of a smile and 3D dental models in dental identification.

The aim of this study was to explore novel odontological methods by combining 2D photographs with 3D models, and to see if 3D imaging in the field of forensic odontology can assist with human identification as an alternative to PM photographs.

3.2 Materials and Methods

3.2.1 Data Acquisition:

All patients referred to the Orthodontic clinic, Dundee Dental Hospital, Dundee, Scotland, attending for initial assessment and those scheduled for de-bonding procedures were identified through the clinic registry by the PI. As a routine procedure, the digital photographs of the patient smiling (pre-and post-orthodontic treated) were taken by a clinical photographer using a Nikon D610 SLR camera. The dental impressions were obtained and the study casts were fabricated on the same day. The dental casts and their corresponding digital photographs of the patient smiling were acquired by the PI over a period of six months. All the patient identifying information was removed and a unique study code was assigned to each dental cast and the corresponding photograph by another researcher. The PI conducted the study and was not provided with the identifying codes until the end of the research.

3.2.1.1 Inclusion / Exclusion criteria:

Patients aged 16 years and above who had consented for their records to be used for research and publication were considered. Photographs with front teeth visible in a smile (from canine to canine) and image quality permitting analysis of the tooth outlines were included. Dental casts that appear to be damaged were excluded.

3.2.2 Study Design:

This study was designed to be conducted by simulating two dental identification scenarios: Scenario A and Scenario B, to test the applicability of this technique across a range of different forensic scenarios. The data collected for Scenario A consisted of dental casts of 31 patients, of which 28 casts were of post-orthodontic patients and three casts were of pre-orthodontic patients. Thirty-one 2D digital photographs of the corresponding patients were obtained. Additionally, four digital photographs (one post-orthodontic patient and three photographs were of pre-orthodontic patients) were included as non-matches.

The data collected for Scenario B consisted of dental casts of 31 patients (different from the sample of Scenario A) which were all of post-orthodontic patients. Of the 31 dental casts, only 24 corresponding / matching (68%) digital photographs (uncalibrated) were obtained. Eleven digital photographs of post-orthodontic patients were included as non-matches (32%) which totalled 35 digital photographs. Additional levels of complexity with more non-matches were introduced into the design so that the uncertainty of identification of matches would require a greater degree of scrutiny on behalf of the investigator(s).

The smile portion in the photographs was cropped using Adobe Photoshop® CC 2017 (Mountain View, California) and saved in Tagged Image File Format (TIFF) format. For the purpose of this study, these "photographs of person smiling" were considered as "2D cases".

Each scenario was analysed in two phases: Phase I - Visual comparison (VC) of 2D-3D images and Phase II - 2D-3D Superimposition. Both, Scenario A and B, methods of comparison were analysed by the PI. One-third of the sample (ten cases - 33%) was assessed by six raters (three forensic odontologists (FOs) – both Scenario A & B, and three MSc. students in Forensic Odontology - Scenario B) for inter- and intra-rater agreement (see Fig. 3.2).

3.2.3 Digitalisation of study models:

The dental casts were laser scanned to create indirect 3D digital images of dental models using R700 3Shape Orthodontic study model scanner (Fig. 3.1) (Copenhagen, Denmark) in .STL format and for the purposes of this study these 3D models were considered as “3D cases”. The time interval between the patient’s photographs and digitalisation of the casts into 3D models was six months.

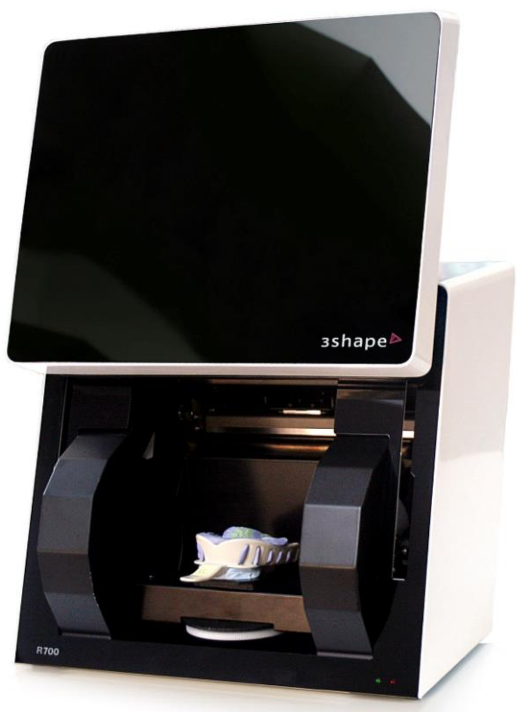


Figure 3.1 R700 orthodontic study model and impression scanner.

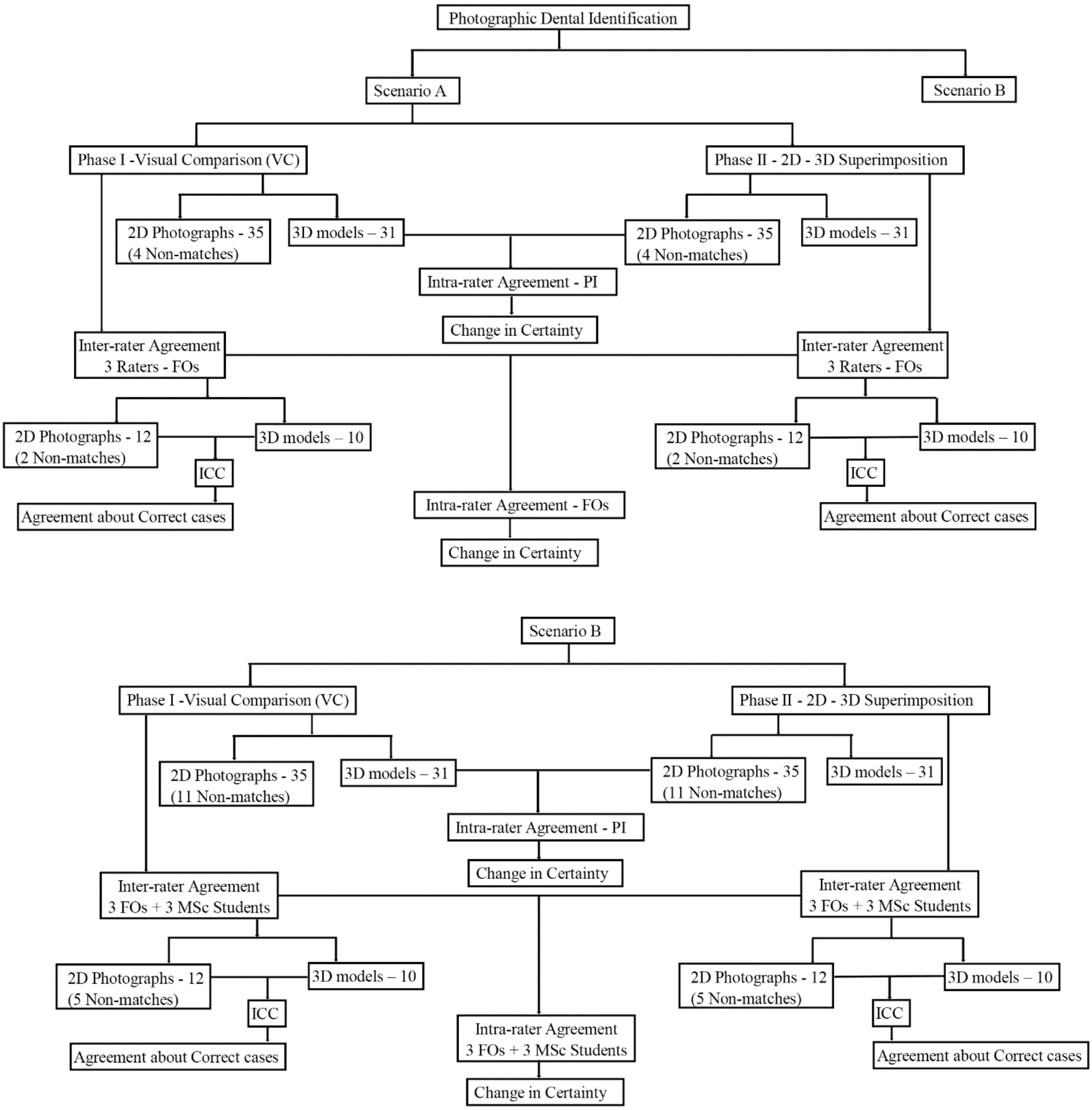


Figure 3.2 The study design shows a dental identification scenario with the methods of comparison, analysed by the PI and raters – Forensic Odontologists & MSc. students.

3.2.4 Scenario A:

3.2.4.1 Phase I- Visual Comparison (VC):

Thirty-one 3D dental models were visually compared with 35 digital photographs (2D cases) showing upper and lower front teeth (canine to canine) by the PI.

The methods of comparison is described below. Dental features analysed during visual comparison and 2D-3D superimposition were: tooth size, shape, incisal contours and alignment within the arch.

An Overview of the 2D-3D comparison technique is presented here.

1. The 3D model (STL file) was imported into 3D Rhinoceros 5.0 software (Robert McNeel & Associates, Seattle, USA, 2018) which enabled orientation of the dental model in 3D (Rhinoceros-3D, 2018).
2. The folder containing 2D photographs of the person smiling (cropped) was opened separately (with Windows Photo Viewer) and viewed for comparison.
3. Each 3D model was compared with all the available 2D photographs by visual comparison – characteristic dental features visible in the image were analysed.
4. The conclusions/opinions reached were based on the INTERPOL DVI guidelines (INTERPOL, 2018) as follows, Identity Established, Probable, Possible, Excluded and Insufficient evidence.
5. This procedure was repeated for all the 3D models.

The INTERPOL conclusions that were available to the odontologists following comparison of PM and AM dental records include:

a. Identification established (absolute certainty the PM and AM records are from the same person).
b. Identification probable (specific characteristics correspond between PM and AM but either PM or AM data or both are minimal).
c. Identification possible (there is nothing that excludes the identity but either PM or AM data or both are minimal).
d. Identity excluded (PM and AM records are from different persons).
e. Insufficient evidence (neither PM nor AM comparison can be made).

3.2.4.2 Phase II: 2D-3D Superimposition:

After a wash out period of four weeks, the second phase of comparison was conducted by the PI using 3D Rhinoceros 5.0 software. 2D photographs were superimposed upon the 3D digital models, see Fig. 3.3 and 3.4. Each 2D photograph was imported into the 3D Rhinoceros imaging software for 2D-3D superimposition.

1. Each 2D photograph was imported into the 3D Rhinoceros imaging software for 2D-3D superimposition.
2. As all the photographs are of frontal view and were uncalibrated, a linear measurement of the width of the upper right/left central incisor of the 3D model was recorded, which helped as a guide for enhancing the cropped smile image with visible incisors to approximate with the incisors in the 3D model (Fig. 3.3 a).

3. The 3D model was reoriented to correspond to the arch position and teeth alignment in the photograph.
4. The image was made transparent to appreciate the features of the 3D model by reducing the opacity with the help of transparency slider setting. Approximately 45-55% setting is usually sufficient and this was considered as a 2D overlay (Fig. 3.3 b).
5. Once the 2D overlay and 3D model were correctly oriented and anterior teeth outlines from the smile in 2D image superimposed on the teeth visible in the 3D model (indicated by arrows), the outline of the outer margins of every tooth was analysed for degree of correspondence during 2D-3D superimposition (Fig. 3.3 d).
6. Thirty five photographs were superimposed upon each 3D model (31 cases), for a total of 1085 superimpositions.
7. The conclusions/opinions were recorded for all the 3D cases according to the INTERPOL DVI guidelines.

The INTERPOL conclusions that were available to the odontologists following comparison of PM and AM dental records include:

a. Identification established (absolute certainty the PM and AM records are from the same person).
b. Identification probable (specific characteristics correspond between PM and AM but either PM or AM data or both are minimal).
c. Identification possible (there is nothing that excludes the identity but either PM or AM data or both are minimal).
d. Identity excluded (PM and AM records are from different persons).
e. Insufficient evidence (neither PM nor AM comparison can be made).

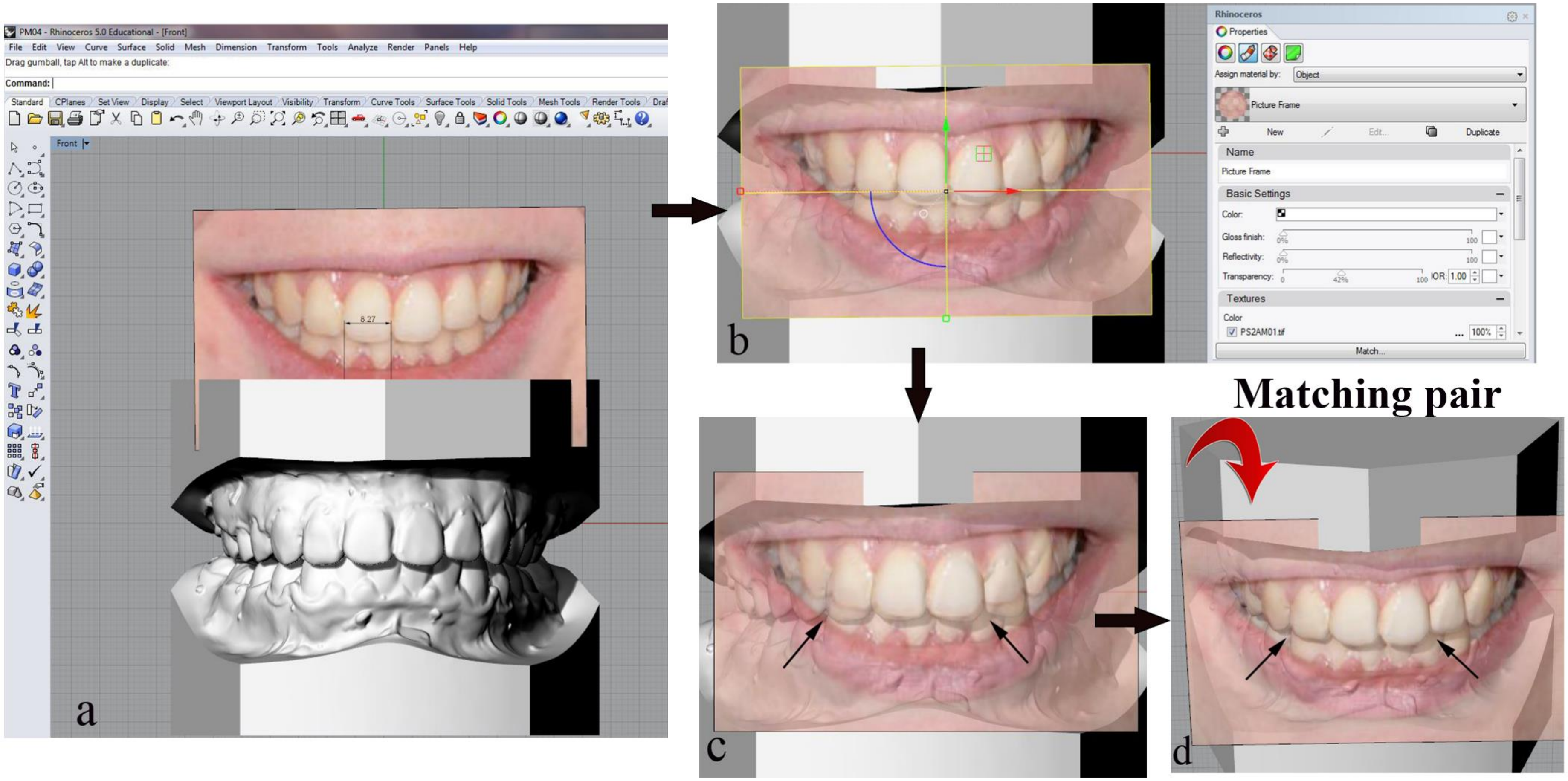


Figure 3.3 2D-3D superimposition using Rhinoceros 3D software – Case 1: **a.** 2D image size approximation with the incisor in the 3D model as a reference landmark; **b.** 2D image superimposed upon the 3D model and converting into overlay; **c,** 2D transparent overlay with underlying 3D tooth outlines (indicated by arrows); **d.** Reorientation of the 3D model (indicated by red arrow) according to the teeth alignment in the smile with incisal contours and tooth outlines useful for analysis (indicated by black arrows).

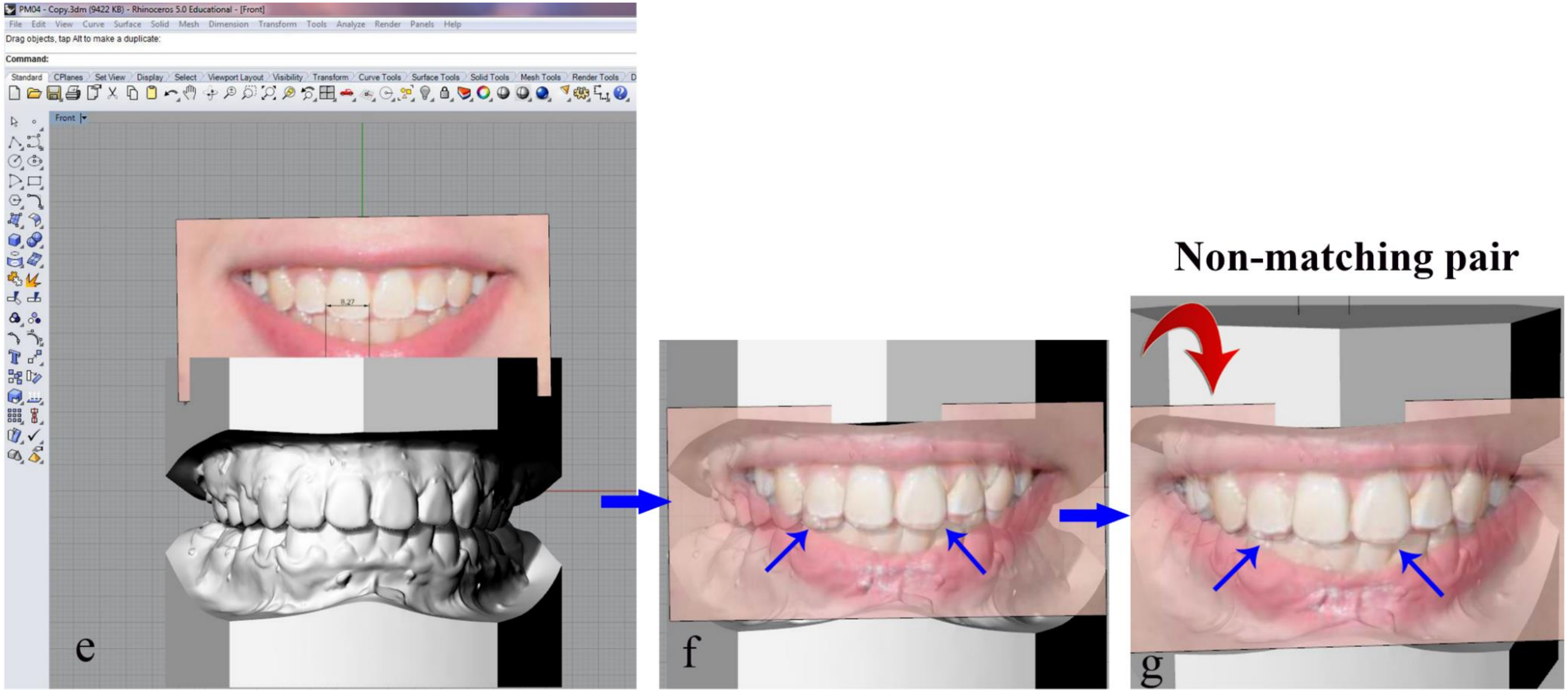


Figure 3.4 2D-3D superimposition using Rhinoceros 3D software – Case 2: **e.** Similar type of dental pattern as in image **a**; **f.** 2D transparent overlay with underlying 3D tooth outlines (indicated by arrows); **g.** Non-alignment of the 2D image tooth contours with the 3D tooth outlines after reorientation (indicated by blue arrows).

3.2.4.3 Inter-rater Agreement (Scenario A):

Ten 3D models were selected at random using online random number generator tool from the 31 3D models' pool of Scenario A by the PI. Ten 2D photographs corresponding to the selected ten 3D models plus two non-matching photographs of post-orthodontic patients (a total of 12 2D photographs) were provided to three raters who were qualified and experienced forensic odontologists. The study was performed in two phases; Phase I – Visual comparison and Phase II – 2D-3D superimposition technique as described above in Scenario A. The raters assessed the 2D and 3D images, opinions were recorded for both phases and the results were analysed using an Intraclass Correlation Coefficient (ICC) (2, 1 – absolute agreement).

The purpose of this part of the study was to find out whether the forensic odontologists were able to identify the correct match and to test their agreement with each other.

3.2.5 Scenario B:

Thirty one 3D dental models were visually compared with 35 digital photographs. In this part of the study, the number of corresponding or matching 3D models and 2D photographs were reduced. The study was performed in two phases as described above in Scenario A. The opinions were recorded for both phases (Phase I and II) by the PI and the results were analysed.

3.2.5.1 Inter-rater Agreement (Scenario B):

Ten 3D models were selected at random from the 31 3D models' pool of Scenario B by the PI using random number generator tool as in Scenario A. In this part of the study, only seven out of ten 3D models had corresponding matches from the 12 digital photographs (five were non-matches). These photographs and models were provided to three raters - forensic odontologists. A further seven Master of Science (MSc.) students, who were current students in the department of forensic odontology that had completed the human dental identification module were also invited and three students volunteered to participate in the study. All hold a dental qualification. The forensic odontologists and MSc. students were provided with the same study sample. This study was also performed using the same methods (Phase I & II) as described above in Scenario A with six raters and the results were analysed (again: ICC 2, 1 absolute).

The study hypothesis was that an imaging technique will aid human dental identification by comparing photographs of the person smiling with digital dental models, with methodology reliant upon the alignment of teeth and morphological traits of teeth for any individual.

3.3 Statistical Analysis:

The inter-rater agreement was assessed using ICC (2, 1 absolute) with IBM® SPSS Package Version 22 (New York, USA).

3.4 Results:

Comparison of 3D dental models with 2D digital photographs followed by 3D superimposition.

3.4.1 Scenario A:

3.4.1.1 Phase I:

In the visual comparison of 3D models with 2D photographs (cases), the PI was able to reach conclusions in only 26 cases out of 31 (Table 1); of which one was wrongly concluded (false positive), “excluded the correct 2D match”. In four cases, the PI could not form an opinion.

PI opinion/conclusion	Case(s) by Visual comparison method	Case(s) by 3D Superimposition method
Identity Established	4	11
Probable	6	13
Possible	16	7
Excluded	1*	4 (2D non-matches)
IE /Cannot form an opinion	4	0

Table 3.1 Conclusions reached by the PI from Visual comparison & 3D superimposition methods. One* correct 2D case was excluded – Scenario A.

3.4.1.2 Phase II:

Through the application of 3D superimposition software, conclusions were reached by the PI in all 31 models and were all correctly identified (Table 3.1). There was approximately 50% and 75% increase in the “probable” and “established” conclusion rate, while 50% decrease in “possible” cases. This 3D technique allowed the PI to reach stronger opinions for more cases when compared to visual comparison.

3.4.1.3 Intra-rater Agreement - PI:

A substantial change in certainty among the opinions reached by the PI was observed between the methods of comparison (Table 3.2). No change in opinion was noted in seven cases.

Change of Opinion by the PI:	Case(s)
Probable to Established	5 (20%)
Possible to Established	2 (8%)
Possible to Probable	12 (50%)
Cannot form an Opinion to Possible	4 (17%)
Excluded to Probable	1 (4%)

Table 3.2 Change of Opinions by the PI – Scenario A.

Overall, there was change of opinion by the PI in 24 3D cases with increased certainty and accuracy. The PI was able to analyse an excluded (wrongly concluded) case from the visual comparison method and correctly identified with a change in conclusion using the 3D superimposition technique.

3.4.1.4 Inter-rater Agreement (Scenario A):

Below is an example of a 3D case and the opinions reached by three forensic odontologists for all the 2D cases (photographs) provided for analysis. Codes assigned to the conclusions were; Established-4, Probable-3, Possible-2 and Excluded-1 as shown in Table 3.3.

Various levels of agreement among the raters is seen in Table 3.3, presenting not only the ratings of the correct case but how they rated all the incorrect cases/non-matches. In the below case example, all six raters did not exclude the correct case, however, opinions differed for the other cases. Of the ten 3D cases provided, only seven 3D cases had correct 2D matches while three cases did not.

3D Case	Target Case	**2D Cases**	**Rater 1**	**Rater 2**	**Rater 3**	Rater 1	Rater 2	Rater 3
3D case 1	-	2D Case 1	Possible	Possible	Possible	2	2	2
3D case 1	-	2D Case 2	Excluded	Possible	Excluded	1	2	1
3D case 1	-	2D Case 3	Excluded	Excluded	Excluded	1	1	1
3D case 1	-	2D Case 4	Excluded	Excluded	Excluded	1	1	1
3D case 1	-	2D Case 5	Excluded	Excluded	Excluded	1	1	1
3D case 1	-	2D Case 6	Excluded	Possible	Excluded	1	2	1
3D case 1	-	2D Case 7	Possible	Excluded	Possible	2	1	2
3D case 1	-	2D Case 8	Excluded	Excluded	Excluded	1	1	1
3D case 1	-	2D Case 9	Excluded	Excluded	Excluded	1	1	1
3D case 1	**Yes**	**2D Case 10**	**Probable**	**Possible**	**Probable**	**3**	**2**	**3**
3D case 1	-	2D Case 11	Excluded	Excluded	Excluded	1	1	1
3D case 1	-	2D Case 12	Excluded	Excluded	Excluded	1	1	1

Table 3.3 An example of a 3D case and the opinions reached by three raters (Forensic Odontologists).

3.4.1.5 Phase I – Visual comparison:

A spread of opinions reached for the correct 3D cases is shown in Fig. 3.5. In a total of ten cases provided, the raters (three forensic odontologists) were in complete agreement with each other in three cases and have provided varied conclusions for the rest of the cases through this method. In one case, one of the raters had “excluded” the correct case, while other raters opinion was “possible”.

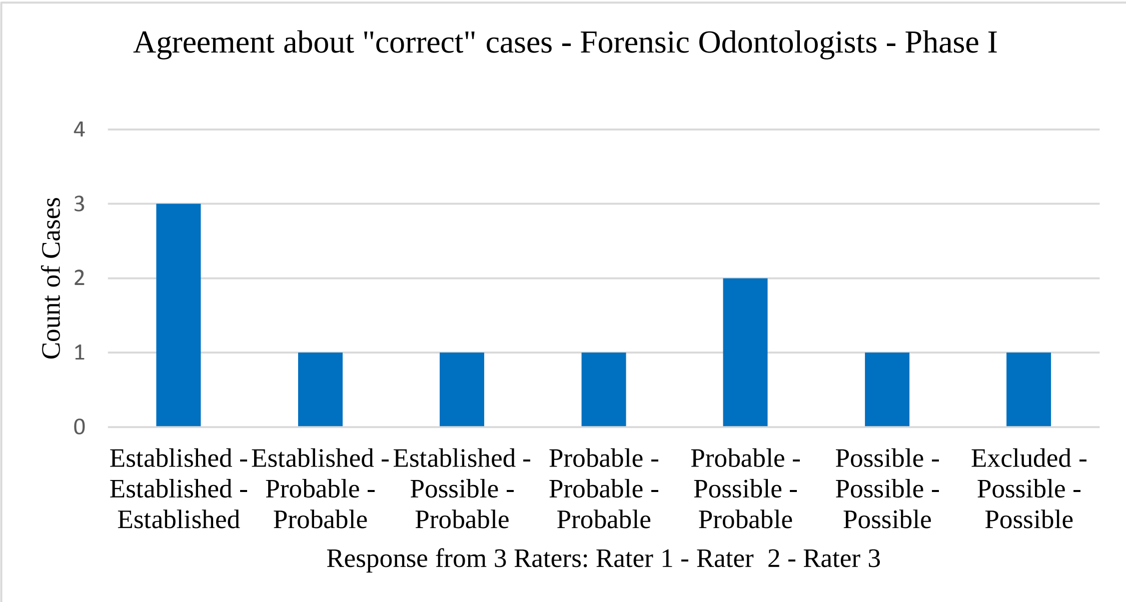


Figure 3.5 Opinions reached for the correct 3D cases by the Forensic Odontologists from Visual comparison method - Scenario A.

3.4.1.6 Phase II: 2D-3D Superimposition:

An increased level of certainty and agreement was observed among the forensic odontologists when using 3D technique (Fig. 3.6). All the "possible" and "exclusion" opinions were changed to "probable" improving the accuracy of the identification, except for one case, which was while one case "established".

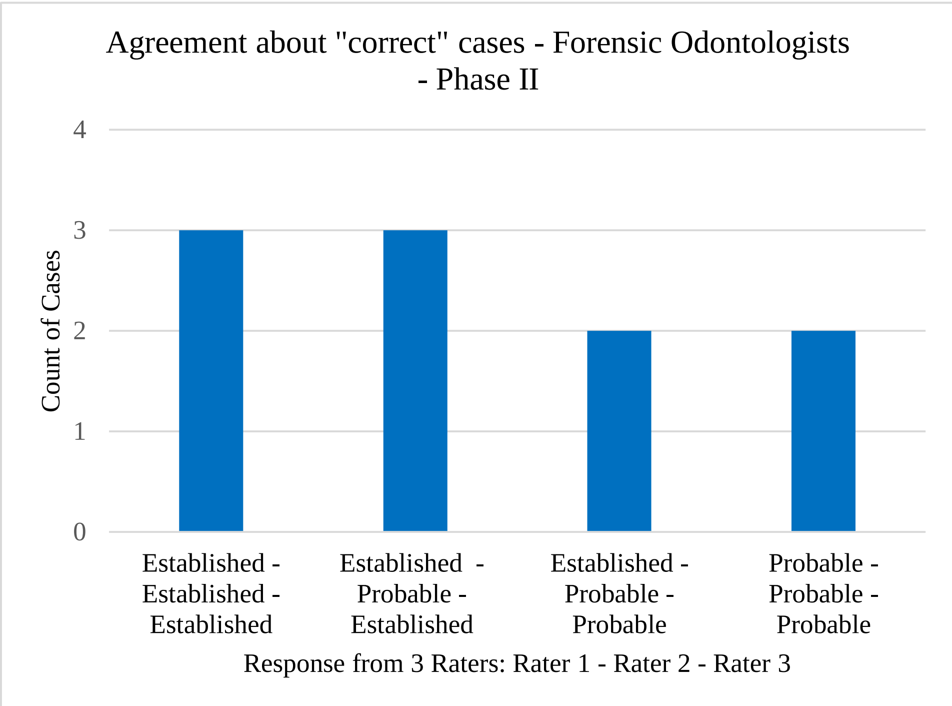


Figure 3.6 Opinions reached for the correct 3D cases by the Forensic Odontologists from 2D-3D Superimposition - Scenario A.

3.4.1.7 Statistical comparison of Inter-rater Agreement – Scenario A: Phase I & II

The intra-class correlation (ICC 2, 1, absolute) was calculated separately for all the 2D cases (photographs) that were compared with a specific 3D case (dental model). The judgements of the raters were treated as an ordinal measure and converted to a numerical code (see Table 3.3). The reliability of this measure varied depending on the 2D photograph that was being compared.

Rater agreement varied between cases (see Table 3.4). A poor level of agreement was observed in relation to case 5 (ICC - .127), while in cases 6 & 7 raters strongly agree (ICC-1.0), good agreement in cases 2 & 8 (ICC - 0.9) and lower levels of agreement in cases 1, 3, 4, 9 and 10 (ICC below 0.75) with Phase I.

3D Cases Scenario A	**ICC - Forensic Odontologists**	
	Phase I: Visual Comparison	**Phase II: 2D-3D Superimposition**
1	**.686**	**.941**
2	.928	1.0
3	.749	.955
4	.725	.941
5	**.127**	**1.0**
6	1.0	1.0
7	1.0	.955
8	.964	1.0
9	.707	1.0
10	**.599**	**.955**

Table 3.4 ICC scores of Forensic Odontologists - Scenario A.

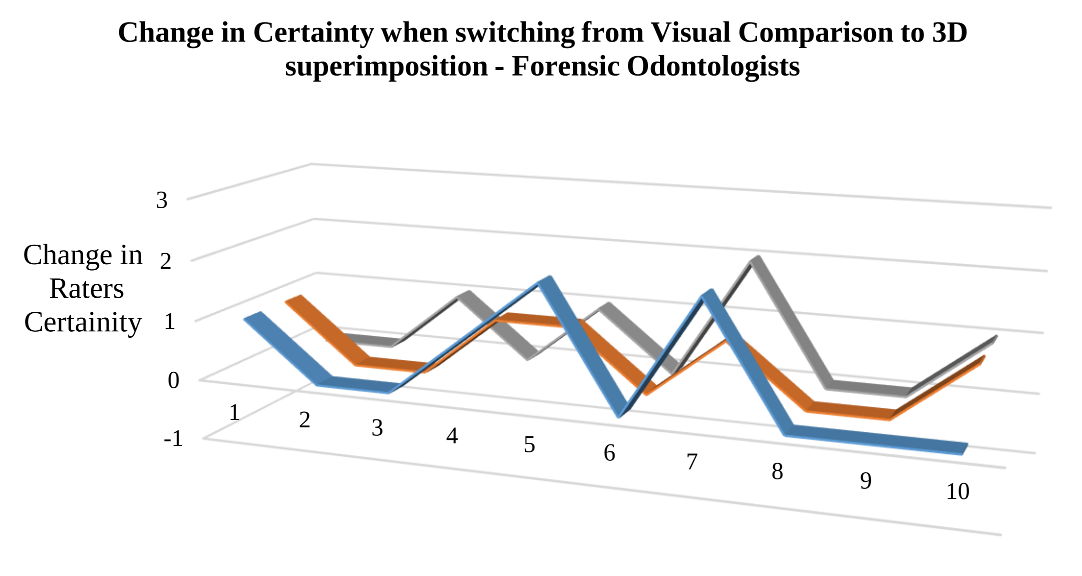
In relation to case 7, high ICC in Phase I (Table 3.4) was due to a common agreement on the conclusions reached for that particular 2D photograph where all three raters opined as “possible” and “excluded” the rest. When using 3D, the opinions changed to higher certainty i.e. “probable” and “established” leading to a lower ICC in Phase II.

High ICC score values near to 1.0 indicates two things; different measures agree with one another, and within the individual measures of any one rater there is sufficient variability in the scores that could differentiate one entity from another. A low ICC score could be due to low agreement or insufficient variability or a combination (Koo and Li, 2016).

3.4.1.8 Intra-rater Agreement (Scenario A):

The change in rating made by a rater was expressed numerically (see Table 3.3). There was an increase in certainty among the opinions reached by the forensic odontologists when using the 3D software (see Fig. 3.7). In this scenario, three forensic odontologist raters, each represented by a coloured ribbon. Ten comparisons per rater, numbered along the horizontal axis. Vertical axis represents the change in opinion between the visual comparison and the 3D superimposition.

It is evident that all the raters have changed their opinions in four cases of the total ten cases provided (Fig. 3.6). No change of opinion is seen as 0, any change from lower to higher certainty as 1, 2, i.e. Possible to Probable as 1 and Possible to Established as 2. For case number 5, rater 1 who had excluded the correct case in visual comparison method have changed to probable. In three cases, raters 1 & 3 were able to opine as “established” when using 3D technique from a “possible” or “probable” state, while rater 2 had been able to improve the certainty of opinions reached. For cases 2,6,8,9 all 3 raters had no change in their opinion, and in case 7 all increased their certainty. For comparison 10, one rater had the same opinion both in visual comparison and for superimposition. But two raters increased the level of certainty of their conclusion by using the superimposition. Also, it is important to note that no rater for any case decreased their certainty using superimposition, they either stayed the same or increased in certainty.



	1	2	3	4	5	6	7	8	9	10
Rater 1 Change	1	0	0	1	2	0	2	0	0	0
Rater 2 Change	1	0	0	1	1	0	1	0	0	1
Rater 3 Change	0	0	1	0	1	0	2	0	0	1

Figure 3.7 Intra-rater Agreement (Scenario A) – Change in Certainty by the Forensic Odontologists.

3.4.2 Scenario B:

3.4.2.1 Phase I:

In the visual comparison of 2D photographs and 3D dental models (cases), conclusions were reached in all cases by the PI (Table 3.5). In this method, the PI had wrongly concluded (false positive) one case; the correct 2D match was "excluded" and other non-matches were considered as "possible" matches.

PI opinion/conclusion	Case(s) by Visual comparison method	Case(s) by 3D Superimposition method
Identity Established	0	9
Probable	18	14
Possible	12	1*
Excluded*	1*	7 (2D non-matches)

Table 3.5 Conclusions reached by the PI from Visual comparison & 3D superimposition methods for 31 3D cases. One* correct 2D case was excluded – Scenario B.

3.4.2.2 Phase II:

Through the application of 3D superimposition software and familiarity of the technique from the Scenario A, it enabled the PI to reach conclusions in all cases efficiently and were all correct (see Table 3.6). There was an increase in the number of cases "established", while the number of "possible" cases decreased. With this technique, PI was also able to "correctly exclude" 2D non-matches; seven 2D cases where the 3D models had no corresponding matches (true negatives).

3.4.2.3 Intra-rater Agreement - PI:

A change of certainty among the opinions reached by the PI was observed between the methods of comparison (Table 3.6). There was a change in opinion in 21 cases and no change in opinion in ten cases.

Change of Opinion, by PI:	**Case(s)**
Probable to Established	8 (26%)
Possible to Established	1 (3%)
Possible to Probable	4 (13%)
Possible to Excluded	7 (23%)
Excluded* to Possible	1 (3%)

Table 3.6 Total change of opinions by the PI – Scenario B.

3.4.2.4 Inter-rater Agreement (Scenario B):

The forensic odontologists and MSc. students assessed ten 3D models and 12 photographs (with five non-matches) in both methods of approach, Phase I and II as described in Scenario A.

3.4.2.5 Phase I – Visual comparison:

Of the ten 3D cases provided, three cases (true negatives) did not have 2D matches. The seven "correct 3D model / 2D photograph" combinations were rated differently by both forensic odontologists (Fig. 3.8) and MSc. students (Fig. 3.9). It was observed that the MSc. students "excluded the correct 2D case" and were not in agreement with one another in that 3D case as well as in other cases. There was lower agreement between both groups regarding the opinions reached. Furthermore, two raters from the MSc. group "excluded" the correct match (false positive).

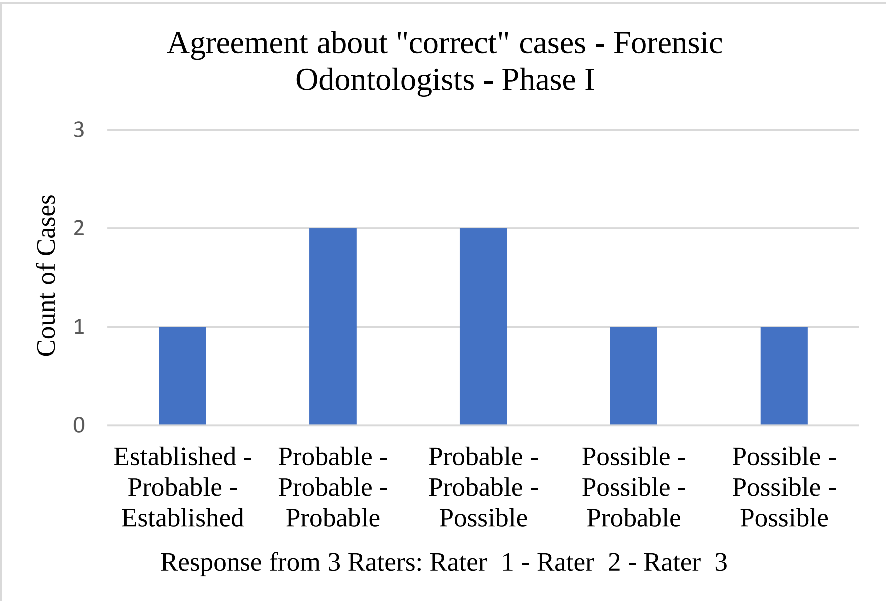


Figure 3.8 Opinions of Forensic Odontologists from Visual comparison method - Scenario B.

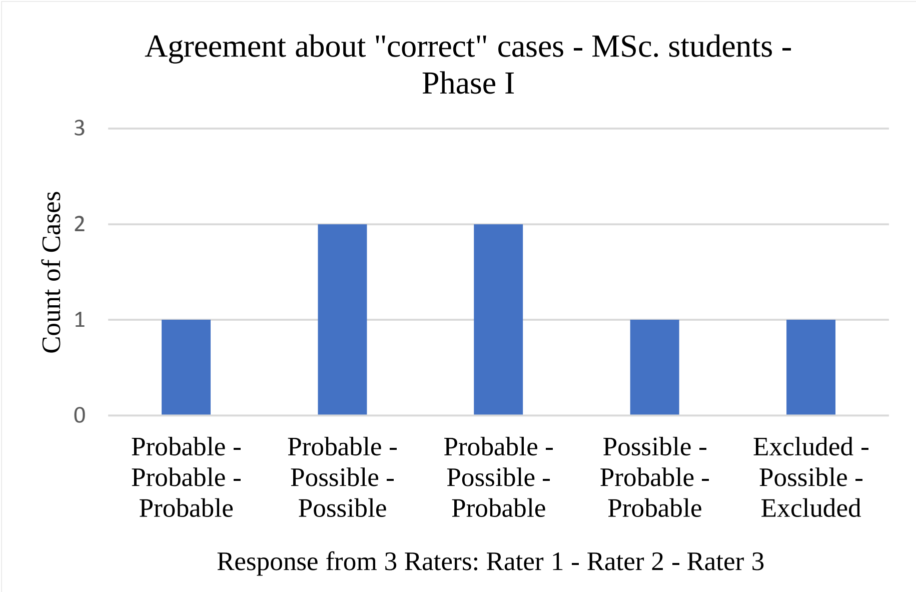


Figure 3.9 Opinions of MSc. students from Visual comparison method - Scenario B.

3.4.2.6 Phase II: 2D-3D Superimposition:

There appears to be good agreement between forensic odontologists and the MSc. students when using the 3D technique. There was an increase in established cases in both groups as seen in Fig. 3.10 and 3.11.

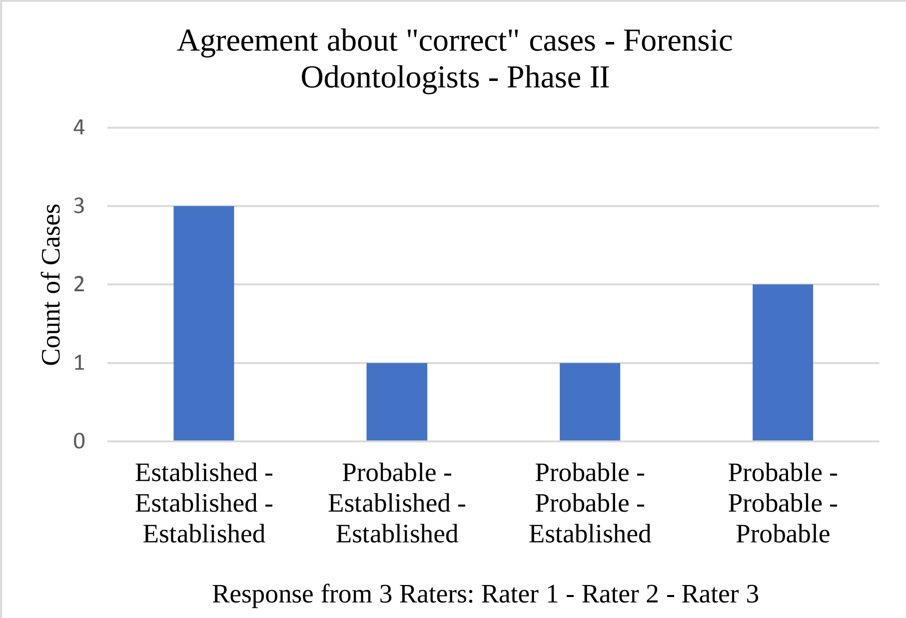


Figure 3.10 Opinions of Forensic Odontologists from 2D-3D superimposition - Scenario B.

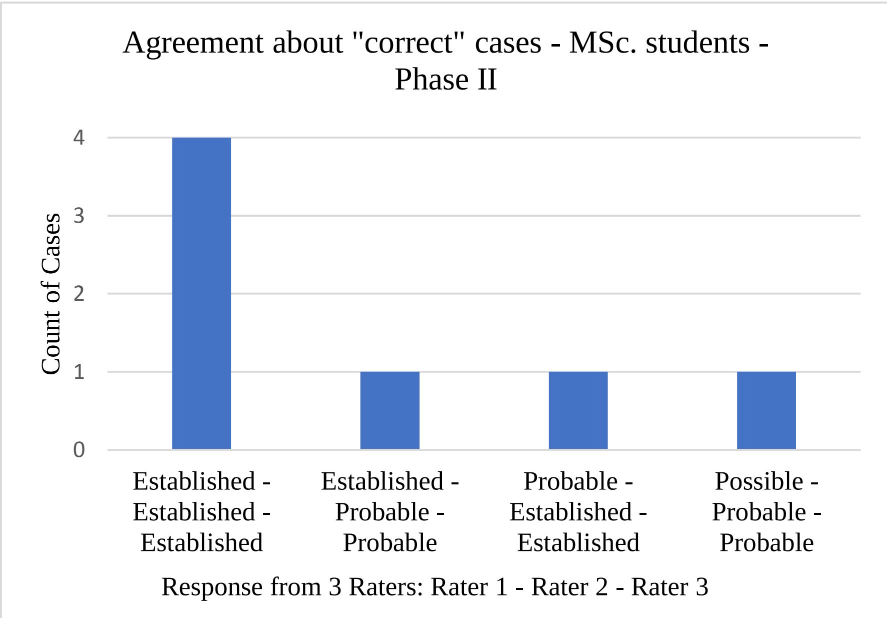


Figure 3.11 Opinions of MSc. students from 2D-3D superimposition – Scenario B.

3.4.2.7 Statistical comparison of Inter-rater Agreement - Phase I - Visual Comparison:

ICC (2, 1, absolute) scores were calculated as before for the forensic odontologists and MSc. students and are reported in Table 3.7. Cases 3, 6 and 10 do not have matching 2D photographs (cases). Of the 7 “correct” cases with corresponding matches, low ICC (less than 0.75) was observed in 5 cases among the forensic odontologists in Phase I. In case 3, there seems to be a small amount of variability, but the low ICC could be a result of the fact that there is low agreement. In cases 6 &10, there is high agreement in terms of “excluding” the 2D photographs, which resulted in reduced variability, hence, again a very low ICC score. The MSc. students (Phase I) have high agreement on a non-match (true negative) in case 3, hence, high ICC. While in case 7, the right match was excluded producing negative results. Overall, low agreement was observed among both the groups, and for most of the cases during Phase I.

3.4.2.8 Statistical comparison of Inter-rater Agreement - Phase II- 2D-3D Superimposition:

Scores were calculated as before for both groups. There were a lot of exclusion scores in relation to cases 3, 6 and 10, (Phase II-Table 3.7) which leads to a reduced or zero variability. ICC score 1.0 indicates that there is variability in the results and there is total correspondence with the right answer. The forensic odontologists and MSc. students demonstrated the effectiveness of this 3D technique and was clearly evident during Phase II.

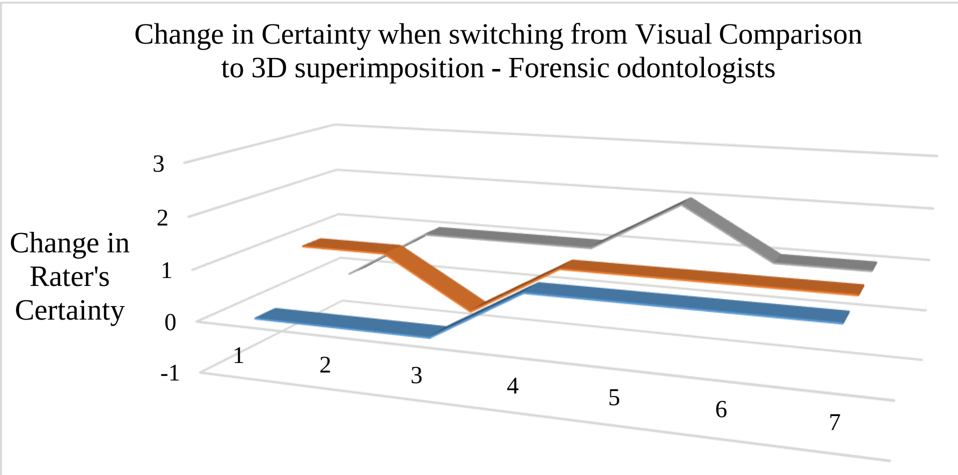
3D Cases	ICC - Forensic Odontologists		ICC - MSc. students	
	Phase I	**Phase II**	**Phase I**	**Phase II**
1	.688	1.0	.597	1.0
2	.741	.955	.333	.955
3	**.358**	**.00***	**.713**	**.00***
4	.835	1.0	.725	1.0
5	.836	1.0	.471	.941
6	**.011**	**.00***	**.175**	**.00***
7	.506	1.0	**-.061**	.889
8	.732	.941	.697	1.0
9	.673	1.0	.513	1.0
10	**.011**	**.00***	**.048**	**.00***

Table 3.7 ICC scores of Forensic Odontologists and MSc. students - Scenario B.

*****The SPSS software produced a result as .00 because of zero variance (all the scores were 1-exclusion) in that square of data.

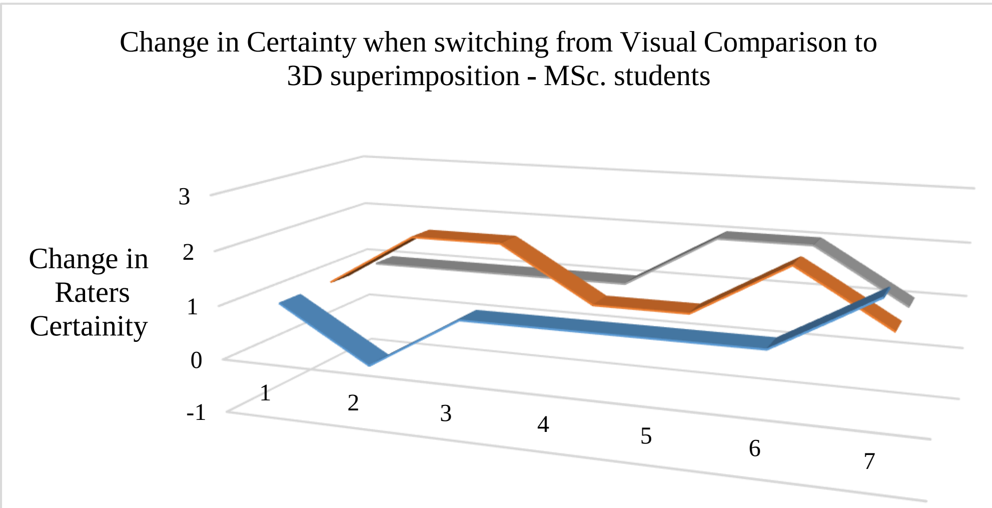
3.4.2.9 Intra-rater Agreement (Scenario B):

An increase in certainty among the opinions reached was observed by both the forensic odontologists and MSc. students when using the 3D superimposition technique. The forensic odontologists (Fig. 3.12) changed their opinions in 16 (76%) of the total 21 cases provided, whereas, the MSc. students (Fig. 3.13), have changed their opinions in 20 (95%) of the 21 cases provided. No change of opinion is seen as 0, any change from lower to higher certainty – 1, 2. With regards to the forensic odontologists, raters 2 & 3 were able to conclude four cases as “established”, and rater 1 concluded “established” for two cases. In five out of seven cases, all the MSc. students were able to express opinion as "established". Rater 1 and 3 had "excluded" one correct case using the visual comparison method, and changed to "possible" when using the 2D-3D superimposition method.



	1	2	3	4	5	6	7
Rater 1 Change	0	0	0	1	1	1	1
Rater 2 Change	1	1	0	1	1	1	1
Rater 3 Change	0	1	1	1	2	1	1

Figure 3.12 Change in certainty of the Forensic Odontologists - Phase II.



	1	2	3	4	5	6	7
Rater 1 Change	1	0	1	1	1	1	2
Rater 2 Change	1	2	2	1	1	2	1
Rater 3 Change	1	1	1	1	2	2	1

Figure 3.13 Change in certainty of the MSc. students - Phase II.

3.5 Discussion:

This study demonstrates the feasibility of using a 2D-3D superimposition method in an identification scenario. Photographs of a smile document valuable information of a person's dentition which could be used as AM dental evidence when dental records are unavailable (Forrest, 2019). Photographic images are 2D projections of 3D objects; thus, objects are difficult to compare if the orientation is not practically identical (De Angelis et al., 2007). This is a major limitation of the 2D–2D comparison methods. It is crucial to reorient the 3D model in the same anatomical position observed in the 2D photograph. A good orientation of the 3D model and a well aligned 2D photograph allows effective comparison during the superimposition process. This method allows users to visually analyse the front teeth, with emphasis on teeth alignment (any malocclusions) and morphological traits. The extent of useful visible dental evidence in an AM photograph when combined with a 3D model as an alternative to multiple PM photographs in a dental identification was explored in this study.

The present study is different to the previous 2D superimposition methods because of the introduction of 3D visualisation of the dental casts as a novel viewing method in photographic dental identification. For instance, the dental superimposition study (De Angelis et al., 2007) requires multiple superimpositions of photographs and this step can be eliminated when using 3D imaging. Bollinger et al. (2009) introduced the GrinLine Technique (GLID) which is a software-assisted manual technique that works best in individual cases or in limited populations of unknowns. The limitation in the study was that the PM photographs were in 2D and should reproduce the perspective variations that could be found in an AM photograph. It also requires multiple PM photographs to be made using step-wise increments in horizontal and vertical angulation. Viewing images in 3D negates this process (Bollinger et al., 2009).

This study assessed the quality of the conclusion reached in a case; comparison of a 3D case with a correct 2D case, and also how the raters judged the non-matches. The results of this study suggest that the inter-rater and intra-rater reliability using 3D superimposition was highest (ICC $\approx$ 1.0). ICC can be treated as a measure of agreement and how much the score of different raters correlate with one another. When applied to subjective assessments like this, it can also be treated as a measure of objectivity. Cases 1, 5, and 10 appear to be subjective, where raters do not agree well with one another (Table 3.4, Phase I). In rest of the cases, raters were reasonably objective as they tend to agree well in Scenario A (Table 3.4, Phase I). The calculated ICC (Table 3.4, Phase II) scores increased when using 3D technique.

Additional levels of complexity with more non-matches were introduced into the design of Scenario B, so that the uncertainty of identification of matches would require a greater degree of scrutiny on behalf of the investigator(s). ICC scores were consistently higher indicating a greater correspondence between rater's judgements with Phase II - 2D-3D superimposition technique. It is noteworthy that both groups demonstrated strong agreement (ICC - 1.0) in cases (3,6,&10) where there was no corresponding 2D match (Table 3.7).

While there is no single agreed value for what constitutes a good or bad ICC (Streiner et al., 2015), one study conducted an ICC in a similar context but using a different technique and reported values between 0.48 and 0.76 representing moderate to good levels of reliability (Zhu et al., 2017). The present study compares very favourably with the Zhu et al. (2017) study because the ICC was between 0.89 and 1.0 when using the 3D superimposition technique (Table 3.7, Phase II). An ICC of 0.89 can be described as good, and 1.0 excellent (Koo and Li, 2016) This result shows that the 3D superimposition technique has achieved better reliability.

The photographs of the subjects obtained for this study were found to be of varying quality. The quality of the 2D photograph, number of teeth visible, therapeutic / morphological alterations of the teeth and any variance or inconsistency with the underlying 3D dentition observed may affect the conclusion reached. All raters reported that 3D approach provided more information for reaching a conclusion than 2D approach. A possible explanation for this is the fact that the raters were able to reorient the digital dental model using the 3D software. A 2D-3D superimposition was achieved by this method and a judgement was expressed by the investigator based on the orientation and the degree of correspondence of the distinctive morphological traits of the two dentitions. Cases with reduced visibility of the anterior dentition in a smile (Fig. 3.14) were also analysed using the 3D method.

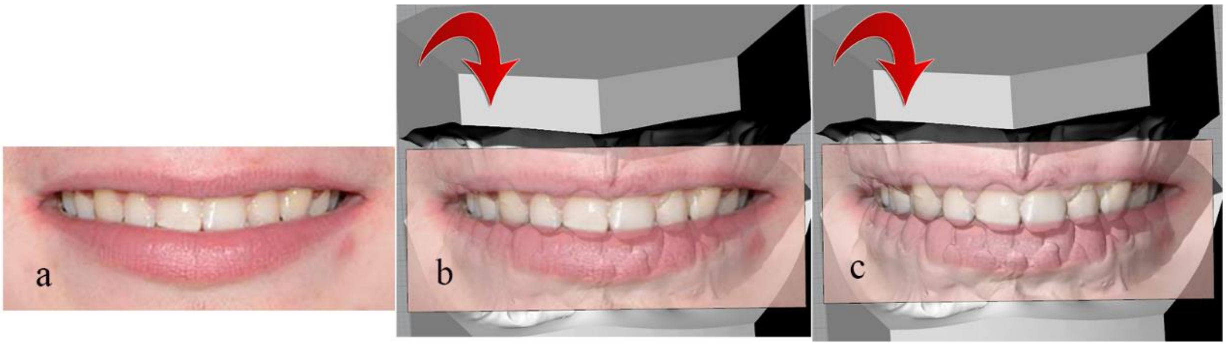


Figure 3.14 A case with reduced visibility of the anterior dentition. 3D model reorientation and superimposition (b and c) enabled the investigator to correctly identify with higher certainty.

The resolution and distortion of the image may be another important limitation when attempting a photographic superimposition. A certain amount of photographic distortion is present when capturing a 3D structure in 2D. Any photograph taken without due consideration could lead to angular distortion. This could be limited when the operator follows a strict protocol by using the right lens and ensuring that the camera is always perpendicular (at 90 degrees) (Evans, 2014), which is difficult to achieve from a forensic perspective. Correction of distorted photographs should be handled with caution. According to the National Policing Improvement Agency guidance (NPIA, 2007) any digital 'correction' of an image with angular distortion may result in the interpolation of the pixels and is considered as 'reconstruction', which can be applied only as a graphical interpretation and should not be presented as a true image. Most of the AM images analysed in forensic practice are of medium to poor quality due to a combination of poor recording systems and optical distortion. Hence, poor quality and severely distorted images (angular distortion) may not permit a 2D-3D superimposition procedure. A study (Moreton and Morley, 2011) also showed that the distance from the camera and resolution both proved to affect the facial proportions. As a result of these drawbacks from 2D–2D comparisons, the 2D–3D comparison method is currently seen as being more reliable (Gibelli et al., 2016).

Metric dimensional parameters have been used to assess variation in human dentition (Bernitz et al., 2006, Johnson et al., 2009), however, this method may not be appropriate to describe dental uniqueness with a quantitative approach. It may be more appropriate to consider the arrangement of teeth in the arch and their relative alignment achieved with this 2D-3D superimposition method. The conclusions provided by INTERPOL are well accepted in the field of forensic identification and have not been quantified into probability or percentages. Also, the sensitivity and specificity of the rater groups cannot be calculated as it requires a yes/no judgement. But that is not the type of outcome the investigator/raters would reach based on the conclusions available. Generally, that would be only possible when a sample data is dichotomous.

It is also pertinent to consider that the present study analysed a very small sample of the population who were all orthodontically treated. The rationale for selecting post-orthodontically treated sample (3D dental models and corresponding photographs) was that the orthodontic treatment aims to correct the position of teeth which improves the anterior teeth alignment and appearance of an individual. A latest study investigated the effect of orthodontic treatment on the uniqueness of the human anterior dentition and reported that orthodontic treatment reduced the uniqueness and increased the similarity between dentitions, with a high number of false positive matches (Dyke et al., 2018). These well-aligned smiles in a photograph could also make the AM and PM 2D photographic comparison procedure difficult. Therefore, a superimposition method was developed to test the applicability of 3D models in identifying the correct 2D-3D matching pairs. The dentitions examined in this study sample were more similar and less unique, but the raters were able to correctly identify all the matching pairs with improved certainty when using the 2D-3D method.

The difference between visual comparison and 2D-3D superimposition match rates and opinions observed through this study were considerable, highlighting the importance of 3D imaging in photographic dental identification. 3D imaging was also used in a recent craniofacial superimposition (CSF) study where 2D AM images were aligned and matched to the 3D skull model (Wilkinson and Lofthouse, 2015). The study aimed to compare the reliability of manual and computerised craniofacial superimposition techniques and its applicability for disaster victim identification. The methodology was based upon the morphology of the skull and the closeness of the match between the skull and the AM images (uncalibrated). The study concluded that CSF method could be a useful tool in narrowing down the possible identifications in closed disasters (known list of victims) and recommended high quality AM images without visible distortions.

The present study was conducted by superimposing 2D digital photographs (uncalibrated) and 3D scanned dental casts of living individuals. The central incisor in the 3D model was considered as a reference in guiding with the enhancement of the 2D image (size approximation) due to their position in the arch and increased chance of visibility in the smile. It is permissible to enhance the whole of a cropped image (NPIA, 2007). The transformation of the dental casts into a conventional 3D format assisted in achieving results with improved accuracy and match rates. This method enabled the raters to “exclude all the non-matches” and have increased the certainty of dental identification using photographs of smile. In addition, this is the first study combining 3D imaging with the traditional 2D photographs of the person smiling as an aid to accurate forensic dental identification. The superimposition based analysis provides appropriate visual corroboration of the findings of feature based analysis.

It is evident in some case reports (Silva et al., 2008, Cardoza and Wood, 2015, Silva et al., 2015a, Silva et al., 2015b) that the identification of the deceased individuals with no dental records were performed by comparing 2D AM photographs of the person smiling and PM photographs of the deceased. Although the method of identification is decided by the investigating odontologist, with the advancements in 3D imaging, this method may be implemented to eliminate the necessity of series of 2D photographs and precise spatial orientation of the PM image in accordance to the AM images, which is an advantage. The American Board of Forensic Odontologists (ABFO) guidelines also recommends to additionally take dental impressions where applicable depending on the preservation of the body (Berman et al., 2013). In a forensic environment, the 2D photographs can be considered as an analogue to AM images while the 3D models of the scanned dental casts as PM models. This may be applied in forensic cases with no dental records by obtaining PM impressions whenever possible and digitising the dental cast.

The evidence presented in this paper suggests that, were this method to be used in a forensic context, it would improve the performance of the forensic expert over the available 2D comparison methods. This method can be regarded as a forensic tool for improving the certainty of photographic dental identification in future. However, further research should be aimed at the performance of this method in a larger sample of different forensic cases and scenarios with more forensic odontologists as raters.

3.6 Conclusion:

This study demonstrated that dental comparison was better using 3D PM technology compared to 2D PM comparison. The transformation of the dental casts into a conventional 3D format increased the match rate significantly, as seen in the comparison of the 2D digital photographs with the 3D dental models. The procedure attempted to reduce the limitations of previous methods like the spatial orientation issues with 2D images and is intended to assist forensic experts with a reliable technique in identification and expressing conclusions on a case when using photographs.

Chapter 4 - 3D imaging as an aid to Selfies to assist with Photographic Dental Identification

4.1 Introduction:

Over the past decade the evolution of technology has enabled individuals to take selfies and share them instantly on social networking sites. Nowadays, smartphones are widely accessible, and it is because of these advanced hand-held devices that selfies have evolved. A selfie refers to “a photograph that one has taken of oneself, typically one taken with a smartphone or webcam and shared via social media”. Selfies have become a global phenomenon on social networks that “selfie” was named the word of the year in 2013 by the Oxford English Dictionary (Dictionaries, 2013). A recent survey shows that 68% of younger teens [13–14 years] report owning or having access to a smartphone and 55% of millennials have posted a selfie on social media sites (Center, 2015). According to Google approximately 93 million selfies were taken each day by android phone users indicating the selfies significant role in online data (Senft and Baym, 2015). However, according to a recent survey, for the past five years, about 1.4 billion smartphones were sold worldwide annually (Statista, 2020).

The first forensic case report (Miranda et al., 2016) where selfie photographs were used to identify carbonised human remains by smile line and image superimposition techniques was in 2D. Rapid technological advances resulted in the introduction of 3D imaging in dental disciplines as digital dentistry has facilitated forensic studies which reported the use of 3D imaging for 2D and 3D comparative analysis (Blackwell et al., 2007, Tuceryan et al., 2011, Franco et al., 2015), however, there are no reported studies that have integrated 3D technology with 2D selfies.

The objective of this pilot study was to evaluate the feasibility of 3D imaging using IOS and 3D scanned dental models, as an alternative to 2D PM photographs to assist with dental identification using selfies.

4.2 Materials and Methods

4.2.1 **2D Data:**

The dental school staff and students were invited to participate in this research and ten participants were recruited by the principal investigator (PI). Each participant provided three selfie images taken from their smartphones within the last year where one image with a smile was used for analysis. The smiling portion in the images were cropped using Adobe Photoshop® CC 2017 (Mountain View, CA) and were considered as "2D Selfies" / cases. The CROP tool allows the smile portion in the selfie to be cropped which is the area of interest. The cropped portion was saved as a TIFF file with 300 dpi resolution using the Image drop down menu (Image – Image size – Resolution -300 Pixels/Inch – Press OK) on the top left side in the Adobe Photoshop tool bar. Two additional non-matching / true negatives selfie images were included with the ten 2D selfies.

4.2.2 3D Scan Data:

This data was collected from two types of 3D scans, intra-oral scans (IOS) and 3D scanned dental models. The IOS were obtained from eight participants using 3Shape TRIOS Intraoral Scanner (Copenhagen, Denmark) while dental impressions of maxillary and mandibular dental arches were obtained from two participants. The study models were cast from the impressions in dental stone and were scanned using the R700 3Shape Orthodontic Study Model Scanner (Copenhagen, Denmark) by the PI to create indirect digital study models in stereolithography (STL) format. The difference in the sample collection was to include different types of scan data in this experimental study. For the purposes of the study, these ten datasets were considered as "3D scans" / cases. All the patient identifying information was removed and a unique study code was assigned to each 3D scan and the corresponding selfie by another researcher. The study was conducted by the PI and the matching codes were provided at the end of the study. Participant Information Sheets (Appendix D) and consent forms (Appendix E) were created and approved by the co-sponsors and ethics service for this research.

4.2.3 Inclusion and Exclusion criteria:

Study participants aged between 25 and 55 years who are able to consent were recruited. Selfies with a minimum number of 5-6 teeth visible in any view (frontal, oblique) were considered. At least one upper central incisor should be clearly visible in the selfie. The image quality should permit the analysis of the tooth outlines were included. Dental casts that appear to be damaged were excluded.

4.2.4 Study Design:

The pilot study was designed to be conducted in a similar way to the photographic superimposition study using 2D-3D method (Chapter 3). The sample was analysed in two phases: Phase I - Visual comparison of 2D selfie-3D scan and Phase II - 2D-3D Superimposition. Both methods of comparison were analysed by the PI using the 3D Rhinoceros 5.0 software (Robert McNeel & Associates, Seattle, USA, 2018).

Step by step technical procedure of Selfie-3D scan comparison and superimposition:

Phase I - Visual Comparison:

Ten 3D dental scans were visually compared with 12 selfies (ten matches and two non-matches) by the PI and the results were analysed.

a. The 3D scan was "imported" into the 3D Rhinoceros imaging software which displays a "standard" four-viewport layout (Menu – File – Import – Browse file on computer). The "front" viewport was activated by clicking with the left mouse button and then the "rendered" mode was selected, Fig. 4.1. In the status bar, the Grid Snap, Smart Track and Gumball was activated by selecting with the left mouse button.
b. The folder containing selfie images (cropped) was opened separately (with Windows Photo Viewer) and viewed for comparison.
c. Each 3D scan was compared with all the available 2D selfie by visual comparison – characteristic dental features visible in the image were analysed.
d. The conclusions/opinions reached were based on the INTERPOL Identification DVI guidelines as follows, Identity Established, Probable, Possible, Exclusion and Insufficient evidence.
e. This procedure was repeated for all the 3D scans.

Phase II: 2D-3DSuperimposition:

After a wash out period of four weeks, the second phase of comparison was conducted by the PI where the 2D Selfies were superimposed upon the 3D scans.

a. Each 2D selfie was imported into the software for 2D-3D superimposition. This was done using a drag and drop method; the selected selfie image was dragged onto the front viewport section of the interface. An “image options” window appeared, the picture frame was selected and the left mouse button was held whilst moving the cursor to enlarge the image to approximate the perspective of the 3D model, Fig. 4.2.

b. The 3D scan was reoriented to correspond to the arch position and teeth alignment in the selfie. To select both the arches “shift” button on the keypad was pressed and held and the left mouse button was clicked on the arches, and to reorient/rotate the arches the cursor was clicked and dragged to the desired orientation as shown in Fig. 4.3. The Top viewport allowed lateral movements (left and right), the Front viewport allowed angular movements (up and down) while the Perspective viewport allowed 360 degrees movement.

c. It was necessary to approximate the teeth size in selfie image to that of the teeth in the 3D model. To superimpose the image upon the 3D model, it was positioned to the front of the scan as shown in Fig.4.4.

d. To scale the image uniformly the image was selected, and the left mouse button was held along with “shift” button on the keyboard whilst moving the cursor as indicated by an arrow in Fig. 4.5. The image was dragged to superimpose onto the 3D scan using the up/down and left/right arrows when selected. Once superimposed, the 2D selfie image was seen as a “surface layer” and the 3D scan as “Mesh” in the software.

e. As all the selfies were uncalibrated, using the “dimension tool”, a linear/angular measurement (left mouse button was held along with “shift” button on the keyboard whilst moving the cursor to measure the tooth width) of the upper right/left central incisor of the 3D scan was recorded, which helped only as a guide for enhancing the cropped smile image with visible incisors to approximate with the incisor in the 3D model, Fig. 4.5.

f. It was crucial to reorient the 3D scan in correspondence to the arch position and teeth alignment.

g. The selfie was approximated / enhanced until the central incisor in the selfie was proportionate with the measured width of the central incisor in the 3D scan. The image was made transparent to a point where it was possible to view the tooth outlines of the underlying 3D scan. This was achieved by the “Properties tool” (clicked with the left mouse button) – Object properties – material – Picture frame - Transparency – Slider setting as required; approximately 45-55% wss usually sufficient, this image was considered as selfie overlay, Fig. 4.6.

h. After the selfie overlay and 3D scan were correctly oriented and teeth outlines from the selfie were superimposed on the teeth visible in the 3D scan (indicated by arrows), the outlines and contours of every visible tooth was analysed for degree of correspondence during 2D-3D superimposition, Fig. 4.7.

i. The perspective view in the software also helped in orienting the 3D scan in a preferred position enabling the dental feature comparison of the superimposed images.

j. The conclusions/opinions were recorded for all the 3D models according to the INTERPOL DVI guidelines as above.

k. This procedure was repeated for all the 3D models. The superimposed images can be exported and saved in JPEG (Joint Photographic Experts Group) & TIFF format.

Characteristic dental features analysed during visual comparison and 2D-3D superimposition were tooth size, shape, incisal contours and alignment within the arch. The study hypothesis was that the application of 3D imaging will assist with forensic dental identification by comparing selfies with 3D scans (IOS and dental models). The methodology of 3D superimposition was based upon morphological traits of an individual and the arrangement of teeth.

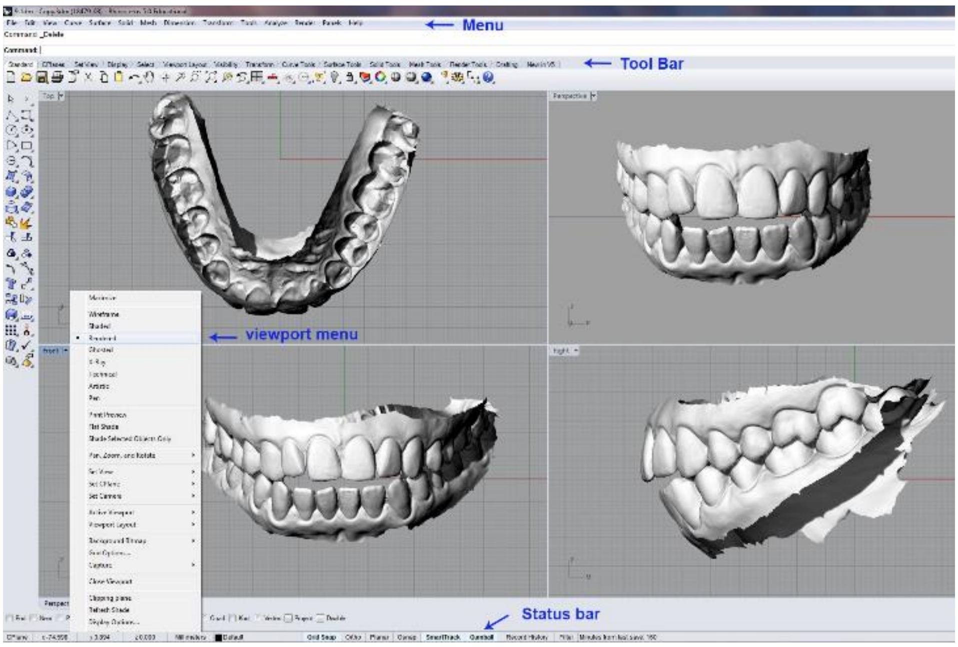


Figure 4.1 3D scan imported into the front viewport of the Rhinoceros software and viewed in rendered mode.

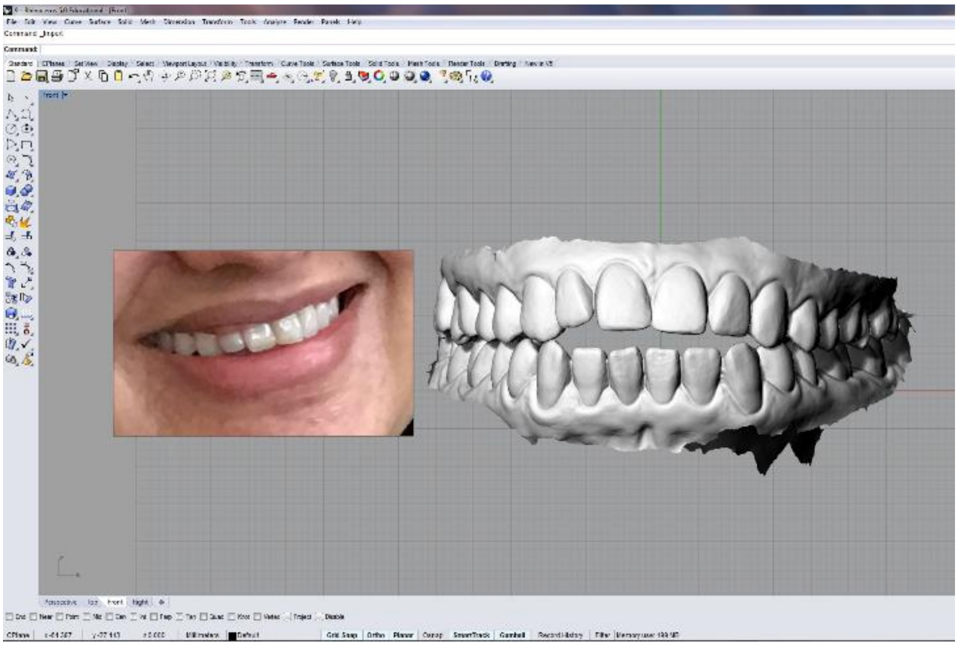


Figure 4.2 The cropped smile portion of selfie was imported using drag and drop method onto the front viewport section.

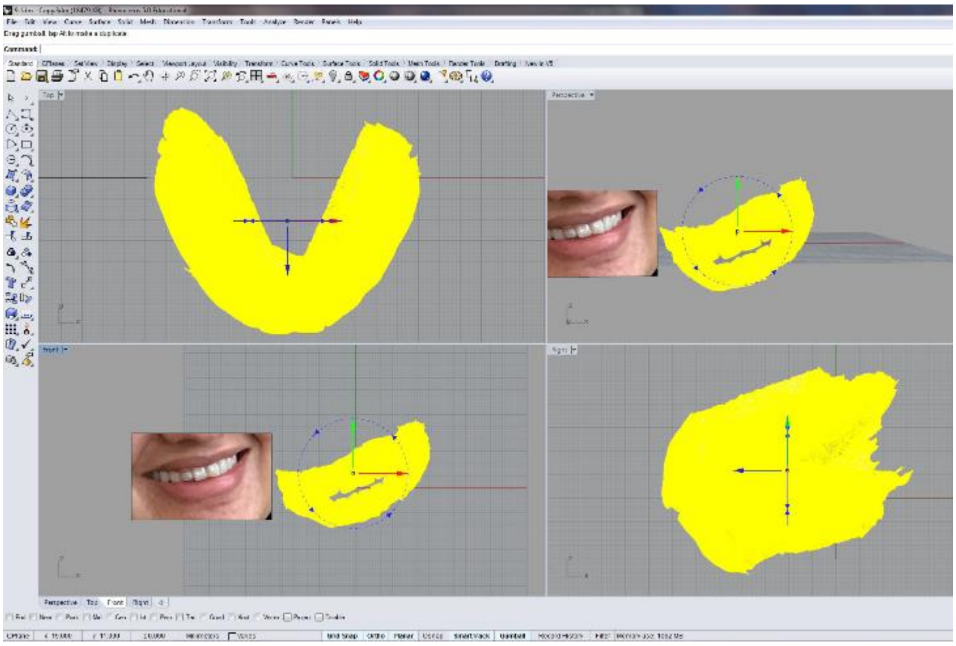


Figure 4.3 Reorientation of the 3D scan to correspond to the arch position and teeth alignment in the selfie.

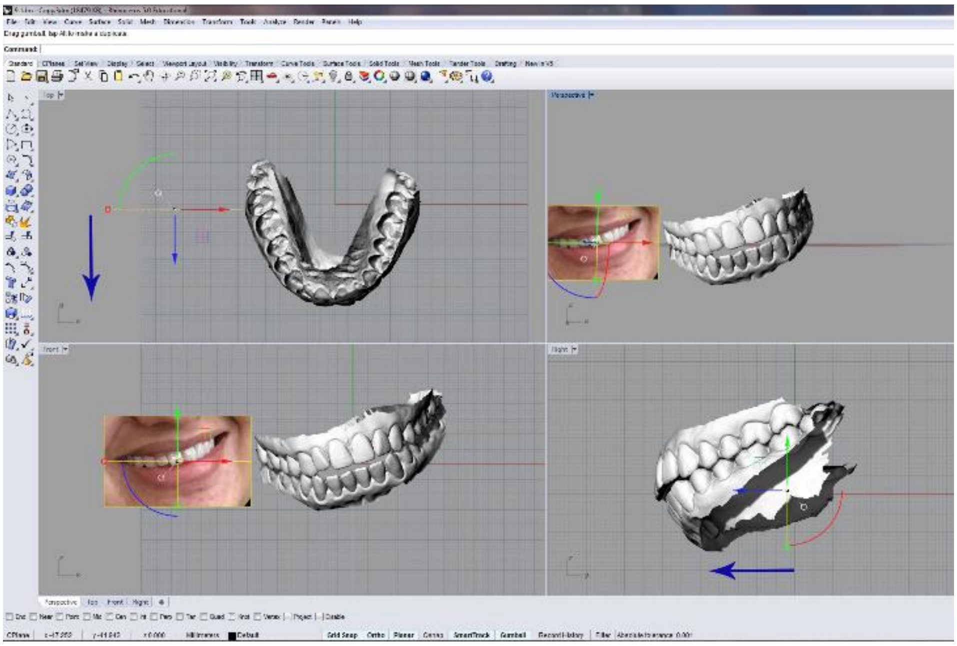


Figure 4.4 Repositioning of the selfie to the front of the scan as indicated by arrow.

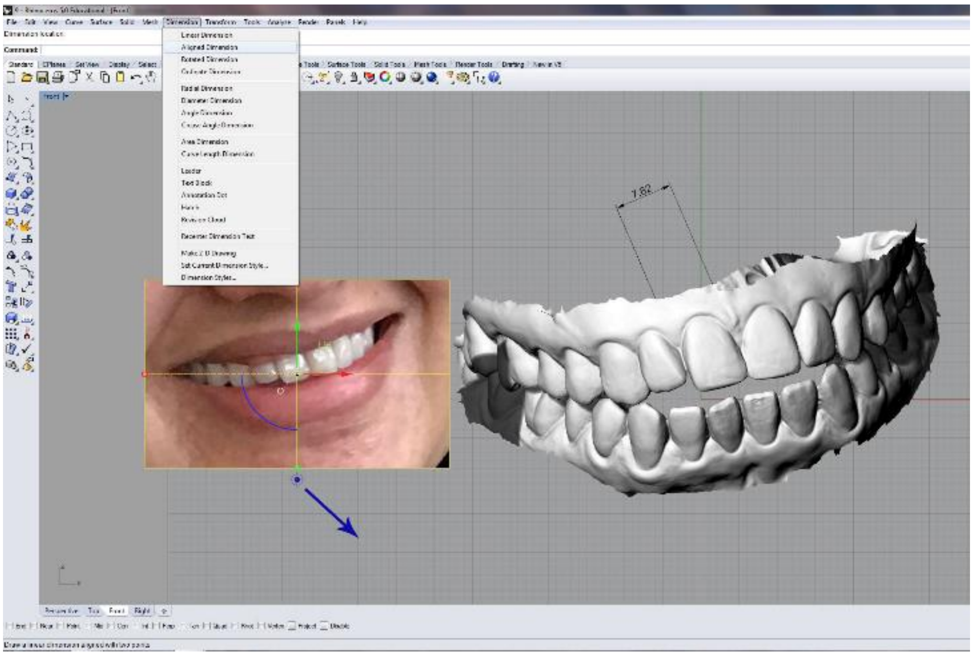


Figure 4.5 Process of enhancing the selfie image for approximation with the 3D scan (indicated by arrow) and measurement (angular) of the central incisor using dimensional tool.

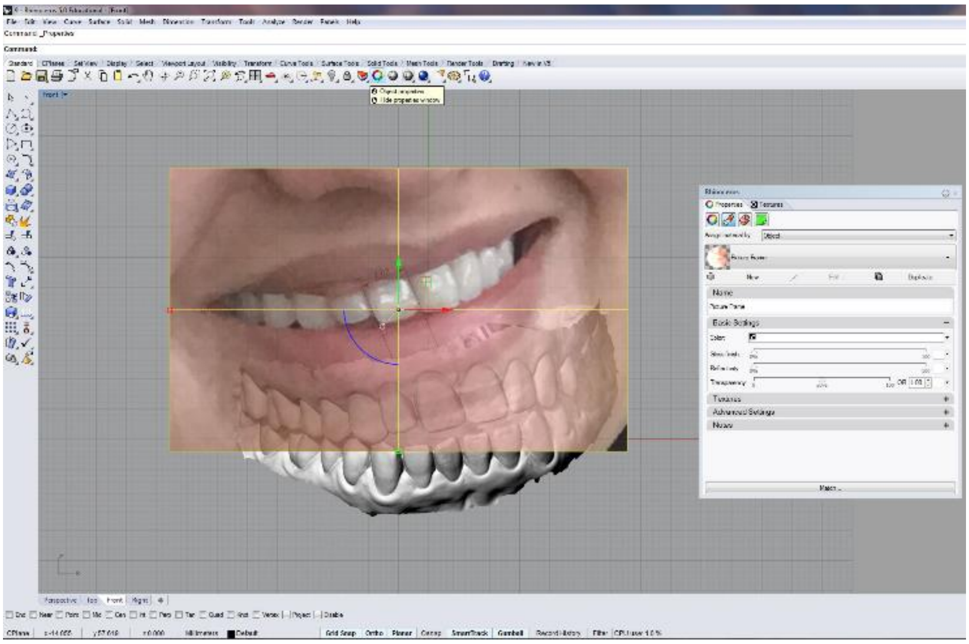


Figure 4.6 Approximation of the selfie with reference to the measured 3D scan. The opacity of the image was reduced using transparency settings.

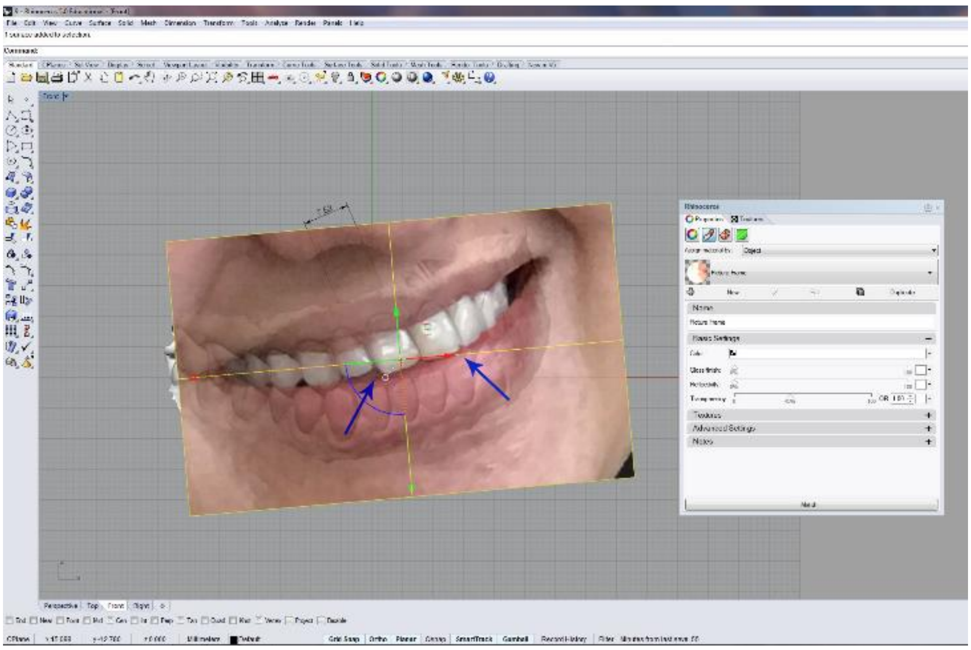


Figure 4.7 Superimposition of 2D selfie overlay upon 3D scan. Finer reorientation and alignments were made. The tooth outlines of the 3D scan were analysed for degree of correspondence with the tooth contours in the selfie image. Arrows indicate well aligned selfies.

4.3 Results:

This method was based on comparison of 2D and 3D images of a simulated identification scenario, one from 2D selfie and another 3D scan followed by selfie-3D superimposition. A total of 120 superimpositions were conducted. The correct codes for the 3D-selfie matching pairs were verified with the conclusions reached by the investigator.

4.3.1 Phase I – Visual comparison:

In the visual comparison of selfies and 3D scans (cases), conclusions were reached in all cases by the PI which ranged from "possible" to "probable" (Table 4.1).

4.3.2 Phase II: 2D-3D Superimposition:

There was an increase in the number of "established" cases and a decrease in "probable" cases with the application of 3D imaging software. Through this method, the PI was also able to "correctly exclude" the two non-matches where the 3D scans had no corresponding matches (true negatives).

Conclusions	Case(s) by Visual comparison method	Case(s) by 3D Superimposition method
Identity Established	0	8
Probable	9	2
Possible	3	0
Excluded	0	2 (Non-matching Selfies)
Insufficient evidence	0	0

Table 4.1 Conclusions reached by the PI from Visual comparison & 3D superimposition methods.

4.3.3 Intra-rater Agreement:

A substantial increase in certainty among the conclusions reached by the PI was observed between the methods of comparison. There was a change of conclusion in nine cases; “probable to established” in eight cases; “possible to probable” in one case and no change in one case. For a given 3D scan, the conclusions reached by the investigator for all the 2D selfies provided for analysis are shown in Table 4.2.

3D Case	Correct Case	2D Cases	Conclusions reached by the PI	
			Visual Comparison	3D Superimposition
3D scan 1	-	2D Selfie 1	Possible	Excluded
3D scan 1	-	2D Selfie 2	Excluded	Excluded
3D scan 1	-	2D Selfie 3	Excluded	Excluded
3D scan 1	-	2D Selfie 4	Excluded	Excluded
3D scan 1	-	2D Selfie 5	Possible	Excluded
3D scan 1	-	2D Selfie 6	Excluded	Excluded
3D scan 1	-	2D Selfie 7	Excluded	Excluded
3D scan 1	-	2D Selfie 8	Excluded	Excluded
3D scan 1	**Yes**	**2D** Selfie **9**	**Probable**	**Established**
3D scan 1	-	2D Selfie 10	Excluded	Excluded
3D scan 1	-	2D Selfie 11	Excluded	Excluded
3D scan 1	-	2D Selfie 12	Excluded	Excluded

Table 4.2 An example of a 3D case and the range of conclusions reached by the PI.

4.4 Discussion:

The general understanding of a “selfie” is that they are often casual in nature captured with a smartphone / camera held at arm's length, as opposed to those taken by another person, which are mainly focussed on the persons face. Hence, selfie images appear to be in various head positions (from straight, oblique and lateral views) with or without a smile. The easy access to camera phones resulted in an increase in photographic self-expression and presentation among the users (Van House et al., 2005) and the emergence of high-quality smartphone photographic technology provided an opportunity to gather photographic evidence for forensic investigations (Biggs et al., 2013). The selfie images generated online through the recent “Selfie Forensic ID” application (Nuzzolese et al., 2018) which was developed as a forensic tool for missing and unidentified persons could be considered as AM image data for future identifications.

The selfies of the participants obtained for this study were of varying quality. On examination of the selfies, it was observed that the number of teeth visible for analysis ranged from 5-6. If the selfie was captured from the participant’s right side (lateral/oblique), the teeth visible were - maxillary first pre-molar (bucco-mesial view) to left lateral incisor; if it was from the front position, teeth teeth visible were - left to right canines (upper anterior teeth); sometimes the mesial part of the left maxillary canine in lateral views and incisal edges of mandibular teeth were visible (Fig. 4.8). The teeth from the maxillary right canine to left lateral (Fig. 4.1-7) and the incisors (Fig. 4.8) (if visible, the mesial parts of the canines) were used for analysis during the selfie-3D superimposition. The quality of the image, number of teeth visible, therapeutic / morphological alterations of the teeth and any inconsistency with the underlying 3D dentition observed may affect the conclusion reached by the investigator.

The disadvantage with 2D images is that they show only one perspective. It is the reduction of the 3D structure into the 2D space of the digital camera which could lead to angular distortion and inaccurate interpretation of an image if the photograph is not captured with due consideration (Evans et al., 2010, Williams et al., 2008). It is permissible to enhance the whole of a cropped image. Any digital 'correction' of an image with angular distortion may result in the interpolation of the pixels which is considered as 'reconstruction' according to NPIA guidance. The reconstructed image cannot be presented as a true image but can be applied only as a graphical interpretation (NPIA, 2007).

Dental superimposition techniques (De Angelis et al., 2007, Bollinger et al., 2009) with 2D AM and PM images were proposed using Adobe Photoshop® imaging software which requires multiple PM photographs to show different perspectives for attaining the anatomical position of teeth in the AM image. To overcome the limitations of 2D-2D comparison methods, a few studies concluded that 3D imaging was more precise, accurate and robust and therefore be explored as an alternative method (Thali et al., 2003a, Evans et al., 2010, Evans, 2014).

This study was conducted using a small sample of selfies and 3D scans of living individuals by simulating a dental identification scenario to demonstrate the applicability of this method. Dental superimposition with 3D imaging has eliminated the need of a series of PM images when compared to the previous 2D superimposition studies and case reports. A similar study also reported the applicability of 3D imaging to test the accuracy and reliability in craniofacial superimposition where facial photographs were aligned and compared with the 3D skull models (Wilkinson and Lofthouse, 2015).

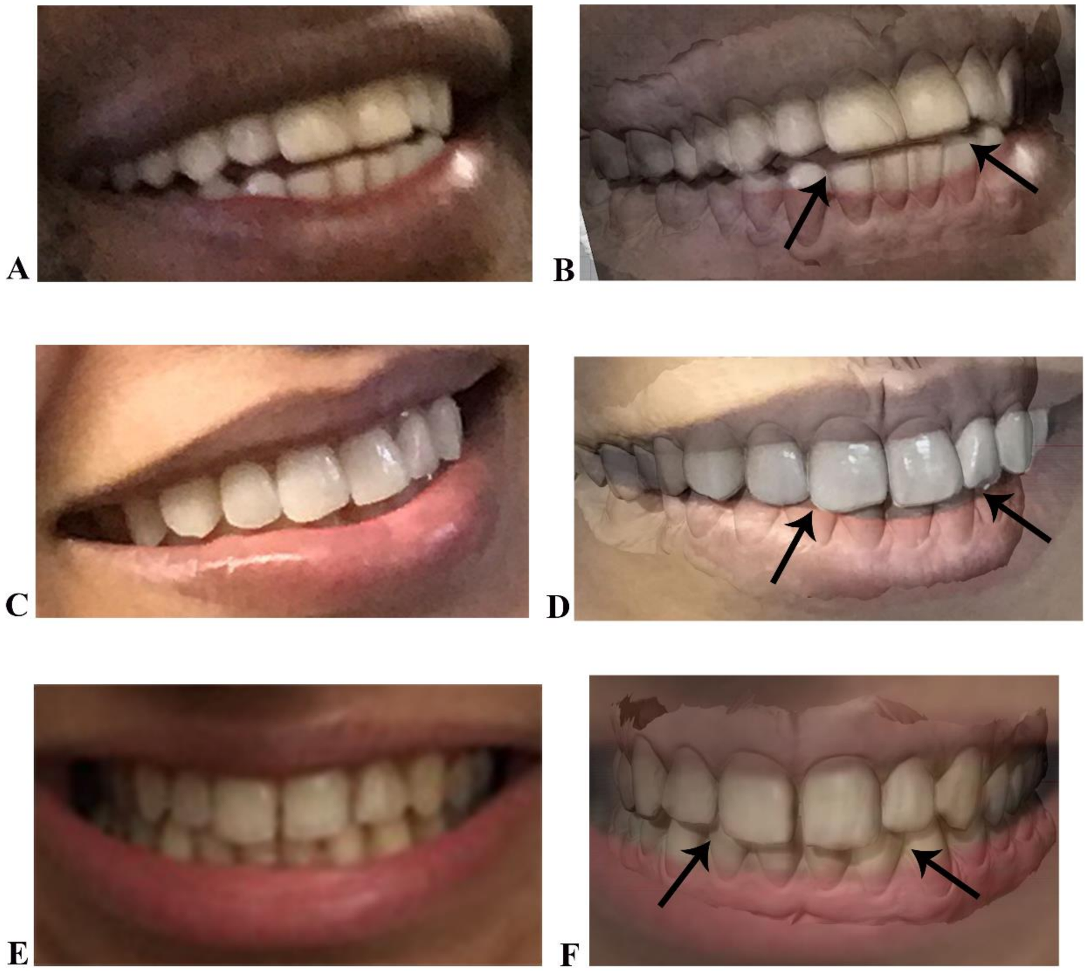


Figure 4.8 Selfies A, C & E shows the varying quality (low to medium) and visibility of the teeth from lateral and frontal perspectives. Images B, D & F shows selfie-3D superimpositions (indicated by arrows).

The feasibility of reorienting and approximating the 3D scan to that of the teeth / arch alignment in the 2D selfie facilitated the superimposition process and assisted with photographic identification. The results of the study show that the use of 3D imaging has increased the certainty of the conclusions reached by the PI and were consistent with the known limitations and abilities of the 2D and 3D comparison methods. Of the 12 selfies available for analysis, there was only one correct match for each 3D scan while the remaining 11 were non-matches.

This study recommends the following measures when using the 2D-3D superimposition method for analysis:

1. To acquire high quality selfie images, preferably more recent frontal views and close-ups.
2. A minimum of 5-6 teeth need to be visible for comparison and alignment with the 3D scan. Visibility of both upper and lower teeth increases the chances of positive identification. Always enhance the whole of the cropped image when approximating with the 3D scan.
3. Images which appear to be severely distorted are to be avoided.
4. To familiarise with the tools in the 3D image analysis software (which permits importing 2D images), in this study – Rhinoceros 3D for ease of performance during analysis.
5. The advantage of the 3D software is the free manipulation of the maxillary and mandibular arches separately; each arch can be individually oriented in line with the arch/teeth position in the selfie image.
6. Positive or established conclusions should be made only after considering the quality of the image, number of teeth visible for analysis, dental characteristics, well aligned teeth/arch and superimposition of the image and 3D scan.
7. This technique could be applied in the “exclusion” of the non-matching images and inclusion of possible matches with large datasets and single case identifications.

4.5 Conclusion:

The rapid dissemination of visual information in the form of selfies as AM data could aid in dental identification. The role of smartphones can be significant, and a selfie or photographic identification in the area of forensic odontology would be identified as an emerging alternative to conventional methods. This technique allows analysis of the front teeth with emphasis on teeth alignment and morphological features. The 3D imaging of PM dental models could serve as a valuable tool in forensic identifications. All the conclusions reached were by the PI. The lack of inter-rater agreement was a limitation to this study. Future studies should focus on large sample size with various selfie angulations.

Chapter 5 - Semi-Automated Methods in Dental Identification

5.1 Introduction

Several dental data coding systems have been proposed for the use in reports and computer-assisted identifications in the field of forensic odontology. The most well known identification applications in the electronic management of dental records were CAPMI (US Army Institute of Dental Research) (Lorton et al., 1988), WinID3 (American Board of Forensic Odontology) (McGivney, 2006), Disaster And Victim Identification ‘‘DAVID’’(Clement et al., 2006), and the Plass Data system - The DVI System International (Holbaek, Denmark) (Torpet, 2005). All have been recommended by INTERPOL to its member countries as they share a common purpose. These systems have primarily automated the text searching of records and require manual processing of data.

Dental radiographs are one of the key components of dental records which facilitate the process of human identification. Studies on semi-automatic and automatic dental identification based on 2D radiographs have been proposed over the last two decades. A semiautomatic dental identification method was introduced which requires manual selection of region of interest in the radiographs. The tooth contours were extracted and the identification result is obtained by matching the PM and AM tooth contours (Jain and Chen, 2004). Later a shape registration method was proposed to align and compute the distance between two teeth on the basis of tooth contours (Chen and Jain, 2005). An automated dental identification system was developed for PM identification using periapical and bitewing radiographs. This was designed to provide automated search and matching of digitised radiographs which was based on the extraction of tooth and root contours and shape matching (Fahmy et al., 2005). However, 2D radiograph-based approaches had several limitations. The tooth segmentation process was time consuming and inaccurate due to the low image quality from blurred dental radiographs. Distortions in tooth shape and arch arising from different imaging angles are significant, thus making it an inapplicable feature in automated 2D radiographic retrieval and identification (Chen and Jain, 2005, Nomir and Abdel-Mottaleb, 2008, Lin et al., 2012).

Various 3D imaging systems have been developed and are being applied in scientific research. Some have been introduced into dental disciplines for treatment planning and evaluation purposes (VECTRA-3D® [Canfield Scientific Inc., New Jersey, USA], 3dMD [Atlanta, Georgia, USA], Maxilim® [Medicim NV, Mechelen, Belgium], Dolphin 3D [Dolphin Imaging, California, USA], Geomagic® [3Dsystems, Morrisville, North Carolina] and GOM Inspect [GOM mbH, Braunschweig, Germany]). Most of this software is used for automated superimposition (best fit alignment) and comparison of 3D models (face and teeth) and are based on surface registration and require initial manual intervention, hence making the process a semi-automated approach.

VECTRA-3D®, is a modular 3D system designed to capture and process stereo images. It consists of two pods, including three cameras (two black and white, and one colour) and a projector in each pod. The soft tissues' facial morphology can be acquired with a 3D stereophotogrammetry imaging system. Dental virtual model and soft tissue facial morphology were digitally integrated with a 3D stereophotogrammetric imaging system. The digital 3D coordinates of three facial landmarks and three dental landmarks were obtained by using Vectra 3D software (Rosati et al., 2010). A pilot study analysed the possible applications of 3D - 3D superimposition to personal identification, a method of superimposition between 3D models of the faces. The 3D model of the face of each participant was obtained by a stereophotogrammetric device - VECTRA-3D® M3 while the facial landmarks were identified by VAM® software (Gibelli et al., 2017).

3dMD is a 3D surface imaging technology with anatomical integrity for clinical application, with ten types of software in the Static-3dMD systems. As CBCT provides only limited information on surface texture, the bone images derived from CBCT and the 3D photographs obtained by 3dMDface System (captures 180-degree of the face, from ear to ear) were combined to evaluate the feasibility of this integration and identify facial regions for 3D registration. It automatically generates a continuous 3D polygon surface mesh in colour (Jayaratne et al., 2012). The 3dMD Vultus software was also used in the superimposition of CBCT models with its corresponding digital dental model that enabled an integrated 3D representation of skeletal structures, teeth, and occlusions (Lin et al., 2013). While another study used this software to perform and measure the surface-based 3D superimpositions of the pre- and post-orthodontic 3D CBCT images (Ghoneima et al., 2017).

The Maxilim® software program was used in the matching process of the digital dental cast with the digital 3D picture of the patient’s face by using a 3D surface matching algorithm (Rangel et al., 2008). This software was also used to perform a surface-based registration of the intra-oral scan and the CBCT model. A distance map, which is a measure of similarity between the 3D models was calculated to assess the accuracy of the models (de Waard et al., 2016).

Dolphin 3D allows visualization and analysis of craniofacial anatomy from data produced by CBCT, medical CT, MRI, digital study model systems, and 3D facial camera systems. Studies aimed to evaluate the precision and reliability of Dolphin 3D voxel-based superimposition and found that this system is fast, reliable and user-friendly (Ghoneima et al., 2017, Bazina et al., 2018).

Geomagic® is an automated metrology software that allows manufacturers to inspect, measure, and compare accuracy of manufactured parts. It has different varieties of software designed for specific usage. For example Geomagic Qualify 12 was used to evaluate the precision of intra-oral digital scanning methods and the discrepancy among the STL files generated (Su and Sun, 2015) and in an in vitro study to assess the reliability, resolution and accuracy of extra-oral dental scanners (de Villaumbrosia et al., 2016). Geomagic verify software was used to evaluate the STL files of the direct and indirect CAD/CAM methods against the reference .STL file using the best fit alignment algorithm. Geomagic Control was used to analyse whether the characteristics of the anterior dentition in the study population were unique (Chong and Forgie, 2017).

GOM Inspect is a CAD interactive software for inspecting and analysing (optical metrology) 3D data from laser scanners and coordinate measurement machines which has standard alignment functions. 3D meshes are calculated from 3D point clouds for visualisation, simulation, surface reconstruction and nominal-actual comparison. GOM also has a variety of industrial grade 3D scanners (ATOS, GOM CT, ARAMIS) which were employed in dentistry (GOM Inspect, 2018). The GOM Inspect software and ATOS scanning system was applied in the forensic research; 3D documentation of skin and bone injuries (Thali et al., 2003b); examination and identification of bite marks in foods (Naether et al., 2012). This system was also used in dental studies; measuring the dental arch dimensions between dento-alveolar Classes I, II, and III malocclusions on 3D models (Slaj et al., 2010); the evaluation of the accuracy of 3D imaging data of a human mandible generated by CBCT and an industrial, non-contact, optical scanner (von Wilmowsky et al., 2015) and to assess the reliability and validity of intra-oral and extra-oral scanning systems (Kirschneck et al., 2018).

A review of various semi-automated 3D systems showed that the applicability of 3D superimposition and evaluation has increased. However, it appeared that most software does not have automated features which facilitate in the automated superimposition process. An initial or manual surface registration is required for this to happen. GOM Inspect is a free version available for comparison of 3D datasets. Hence, an experimental study was conducted to test the performance of the GOM Inspect software for automated identification using multiple 3D dental models.

5.2 Materials and Method:

Five pairs of 3D dental models (maxillary and mandibular) were randomly selected from the research data pool for processing through the software. All the models were in STL format. The GOM Inspect interface is built with a tool bar which allows to import 3D models for comparison. As per the user instructions of the software, the 3D reference models need to be in mesh format and the test or inspection model as CAD body for the alignment and comparison process (Fig. 5.1). The conversion process of the reference to mesh format and later to G3D format for comparison is shown in (Fig. 5.2-5.4). Importing the 3D models by drag and drop method is available but the reference and test models needs to be imported into specific categories (CAD or actual mesh).

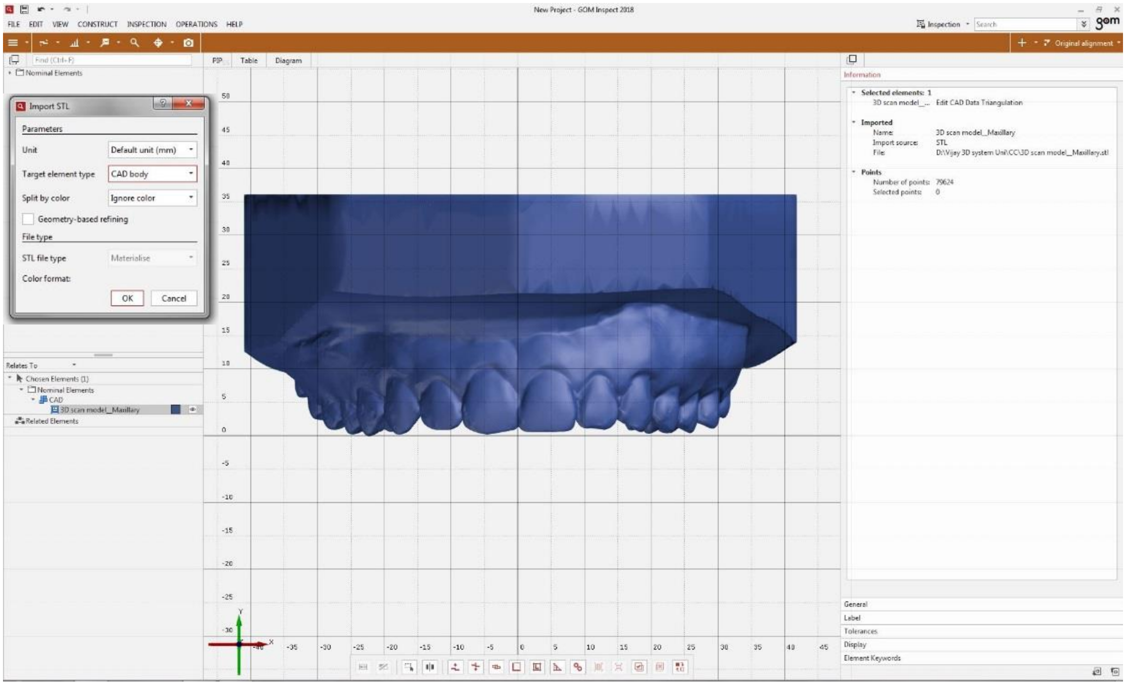


Figure 5.1 3D model imported as CAD body.

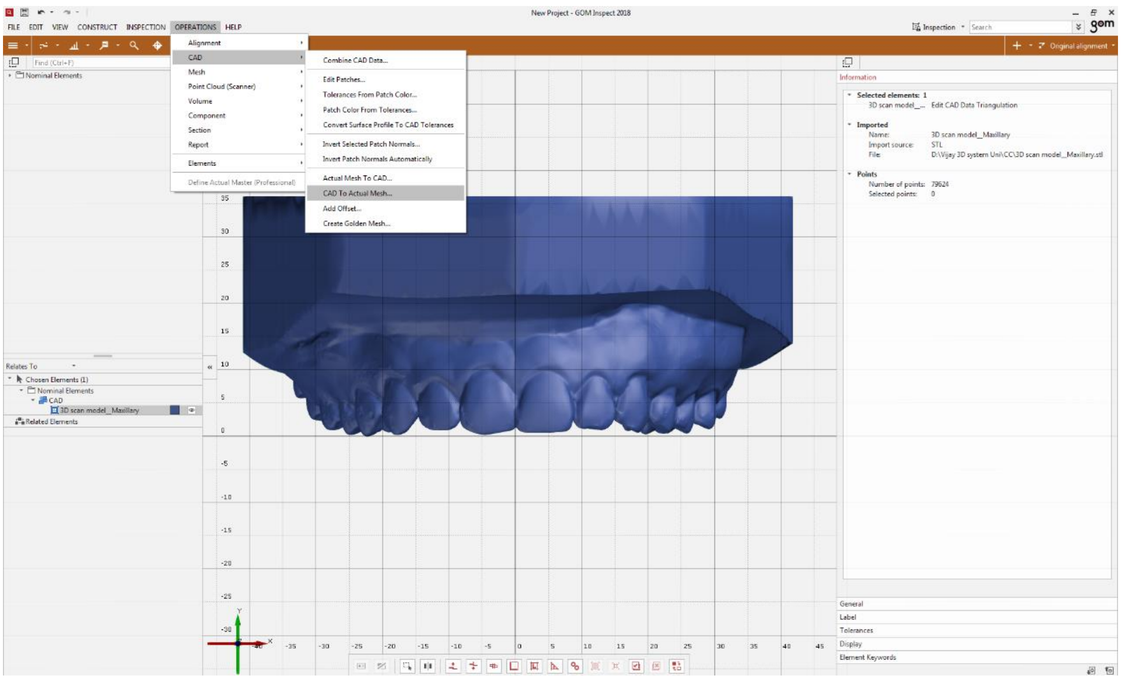


Figure 5.2 Conversion process of the 3D model (CAD) to Actual Mesh (as per the software user instructions).

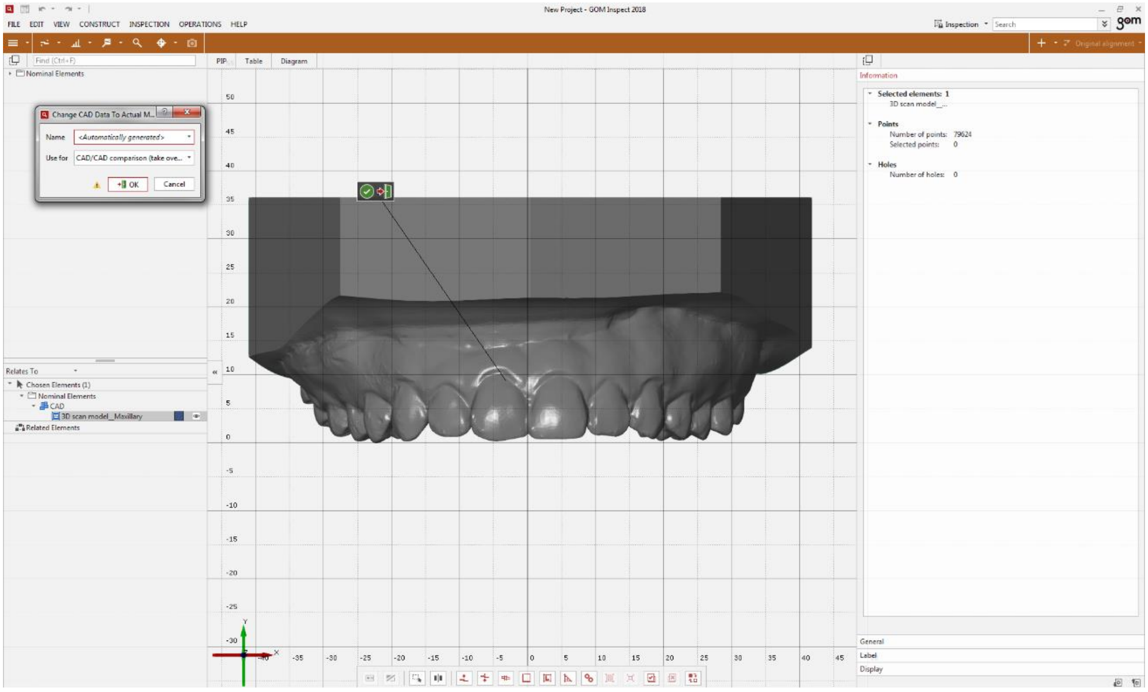


Figure 5.3 Imported 3D model (CAD body) converted into Mesh.

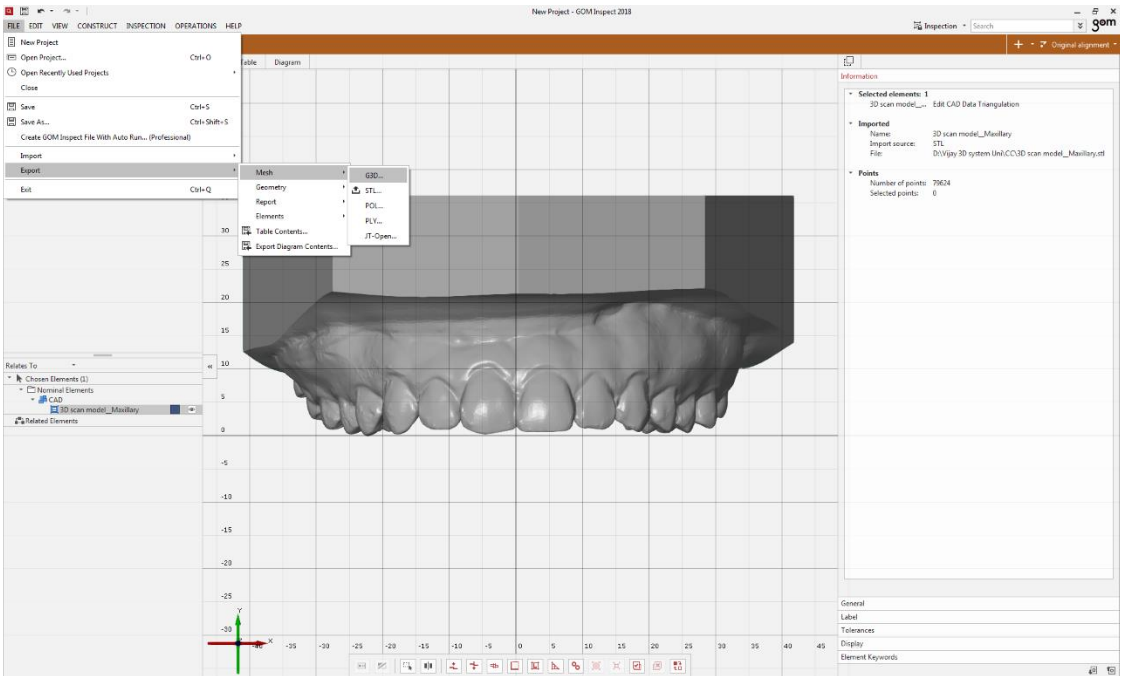


Figure 5.4 3D Mesh exported and saved in G3D format to be used as Reference model.

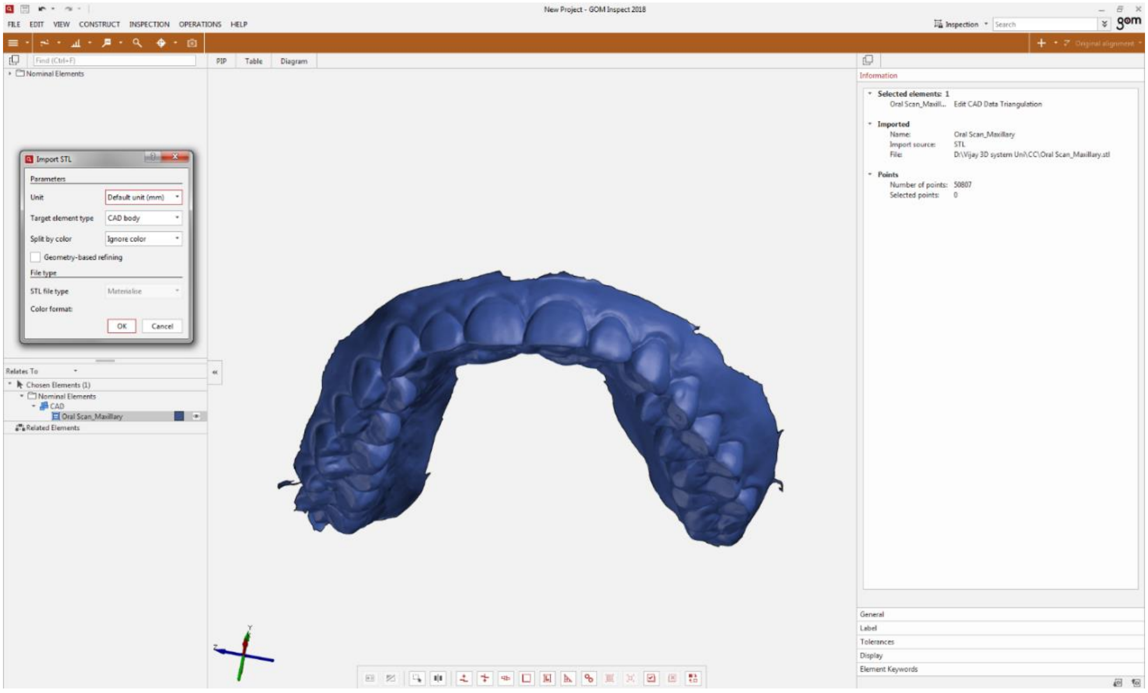


Figure 5.5 Test or unknown scan imported as CAD body.

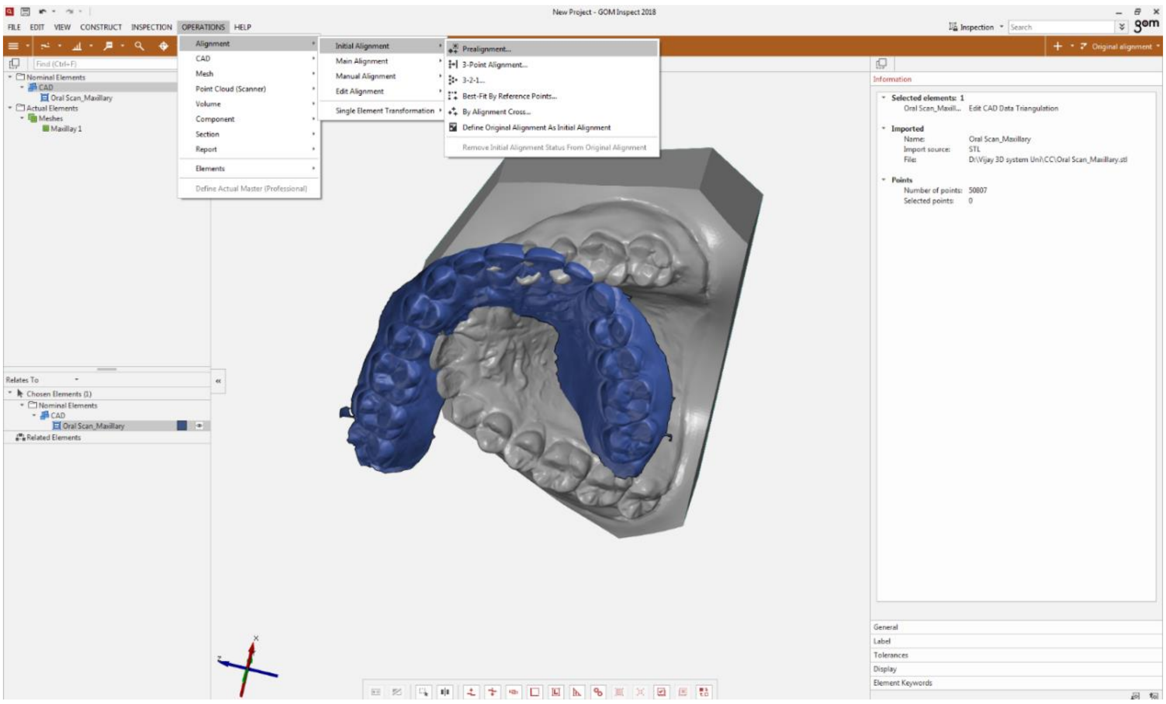


Figure 5.6 Alignment process of the reference (mesh) and test (CAD) models.

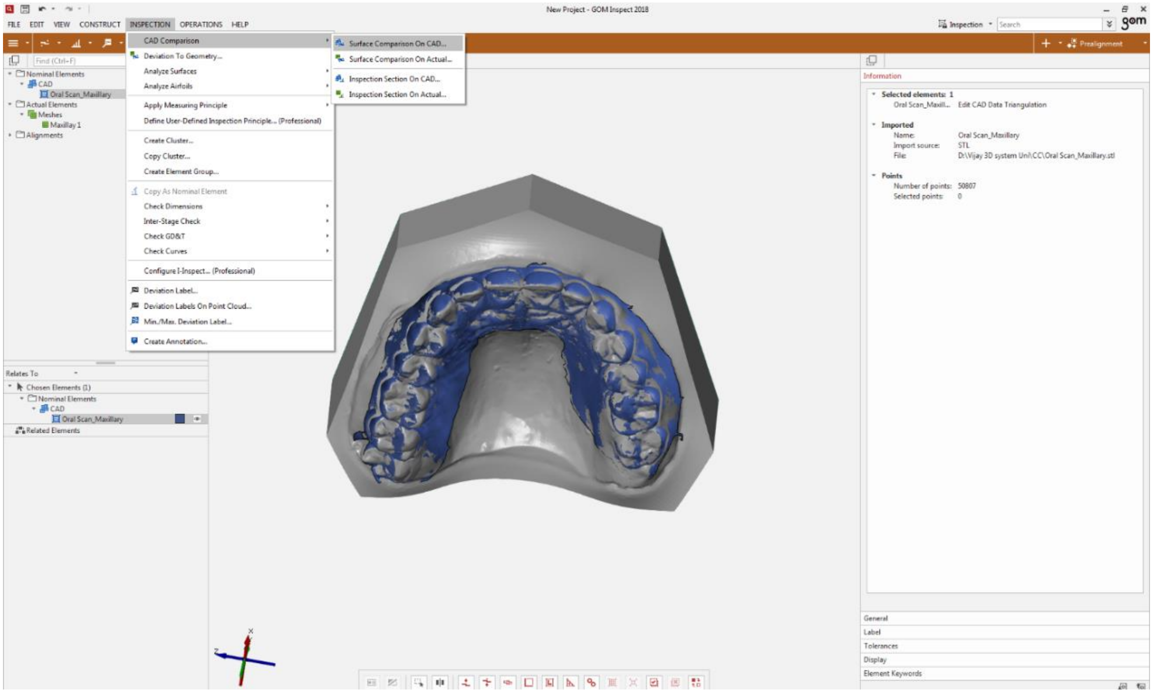


Figure 5.7 Aligned test and reference 3D models.

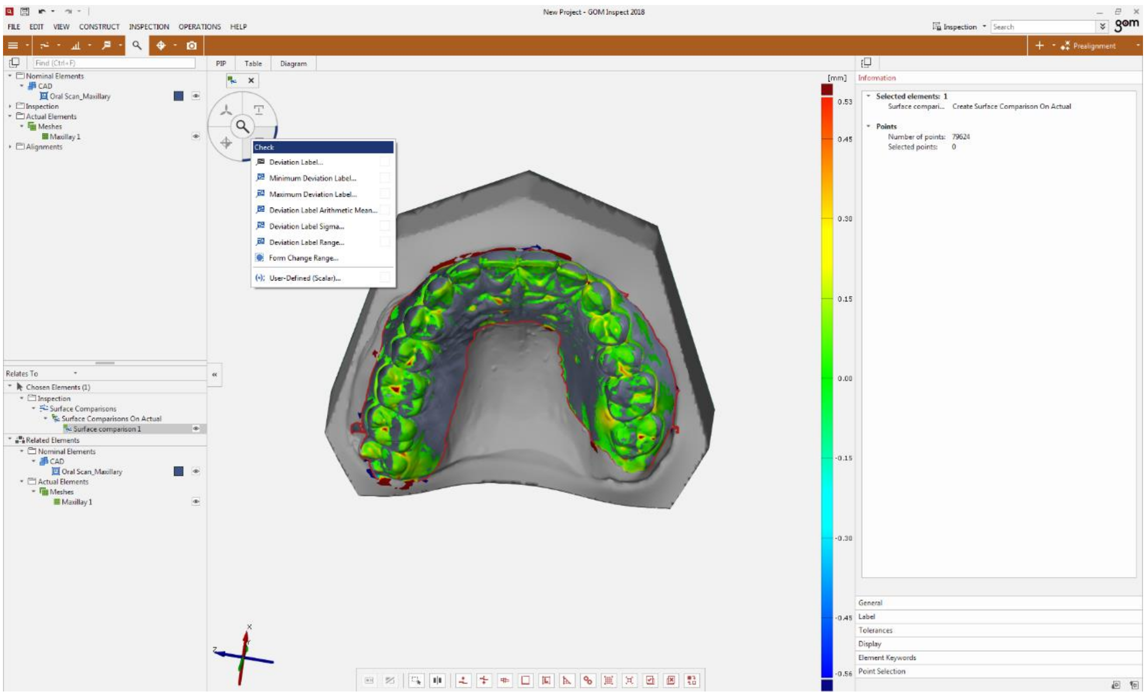


Figure 5.8 Surface comparison of the CAD/test model with the matching reference model / actual mesh.

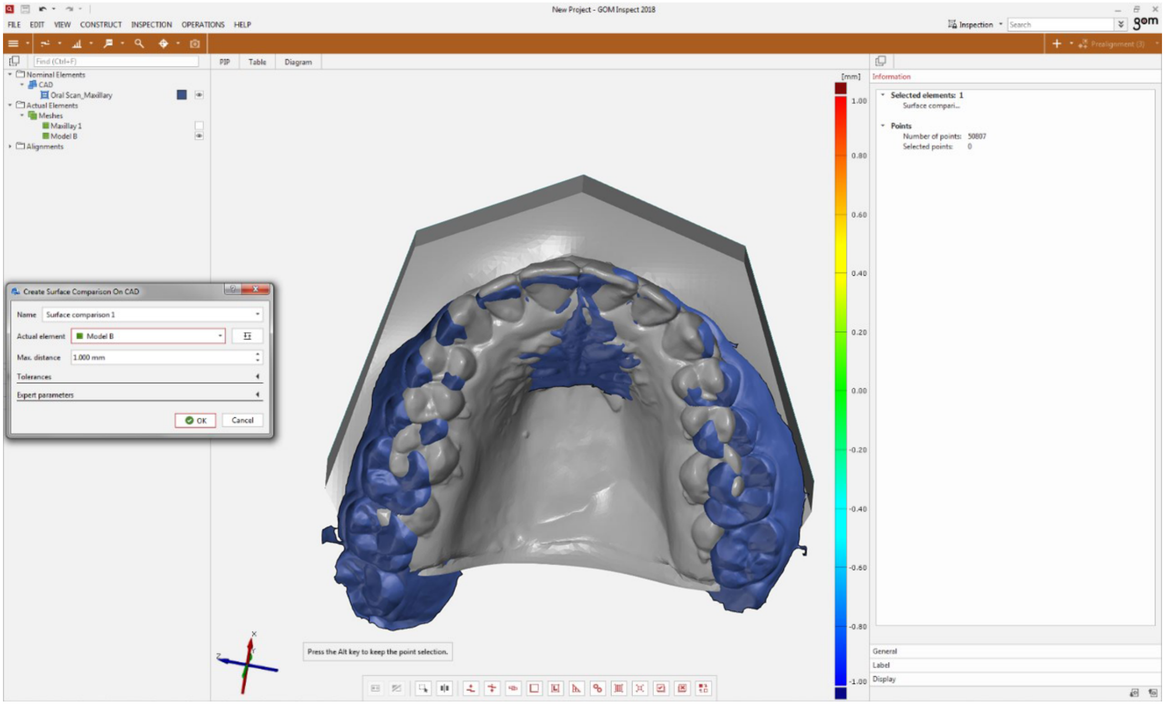


Figure 5.9 Alignment of a non-matching test and reference 3D pair.

When both the reference and the test datasets were imported into the required file formats, a manual intervention is necessary to align the selected 3D pairs as shown in Fig. 5.6. Once the alignment process of both (reference and test) models was initiated by the pre-alignment feature in the operations button, the software computes and superimposes the 3D models based on the best fit process, resulting in an optimal fit between the surfaces (see Fig. 5.7). Once superimposition was achieved, a surface comparison colour map was created, on which the measurements between the datasets can be obtained, with a maximal deviation of 0.5 - 1 mm. The I-Inspect button (Fig. 5.8) helps in finding the suitable measurements such as minimum and maximum deviation on the test model surface. A predominance of green represents a perfect fit between the experimental and the reference dataset, and red and blue indicate positive and negative discrepancies. The alignment of a non-matching 3D pair is shown in Fig. 5.9.

5.3 Results

The software was able to produce a best fit alignment with the corresponding reference model and a non-alignment with a non-match. It was not possible to perform an automated identification with all the five sets of data at once. Only pair-wise alignment and surface comparison was possible through this software. The confirmation of the correct matching pair or superimposition was mainly by visual inspection followed by the maximum and minimum deviation results during the surface comparison.

5.4 Discussion

This experimental study was conducted to evaluate the performance of the GOM Inspect software for automated identification and its efficiency when using multiple 3D datasets. The 3D software discussed in the literature review are very advanced and have intelligent properties developed for a specific function.

With the GOM Inspect software, the operator should be alert and specifically import the reference data into meshes or actual elements and the test models as CAD body or nominal elements. It would not be possible to perform a comparison when both scans are in the same format. Though, multiple 3D data sets can be imported into respective formats, manual selection of the desired pairing is still required for the superimposition. After the alignment, further measurements can be performed. Apart from the measurement of the surface comparison, there are no other quantitative features that indicate or identify the correct superimposition to the operator.

In a forensic context, this software may be useful in single case identifications but not suitable for multiple case scenarios. There is a need for a new automated software that overcomes the limitations of this software.

5.5 Conclusion

In summary, the GOM Inspect software was unable to perform an automated identification with multiple 3D datasets, however, pair-wise comparisons can be made. It required manual intervention and has limited features to indicate when a correct matching pair is visually recognised.

Chapter 6 – Software Development and Testing

6.1 Background

Automation is the process of creating software and systems to replace repeatable processes and reduce manual intervention (IBM, 2018). The early thoughts of Sharkey and Murison (1973) about automating dental records: "What is difficult is to design a method of entry to the computer which can be easily used by the dentist and his assistant, and which can also provide a possible back-up record system" (Button et al., 1999). Since then, with the evolution of automation process and latest advancements in computer technology, opportunities have arisen for a new phase of automation in this digital era. An example in dentistry, CAD-CAM technology created an alternative technique for producing dental restorations.

Using a laser scanner, dental casts can be converted into 3D models (Martin et al., 2015) that may be used in alignment and matching which can be subjected to automated comparative dental analysis. Study models are essential diagnostic records, which help to study the occlusion and dentition. They are valuable for research and forensic purposes as they provide observable, precise geometry of the teeth and jaws (Grippo and Kristensen, 2015). In general, orthodontists maintain the study models of the pre- and post-orthodontic treated patients as part of the clinical records. They should be of good quality and be marked with the date of the impression and the patient's unique identification details (BOS, 2015). Other possible sources of study models would be during the production of mouth guards for sports, an upper removable appliance or functional appliances, bleaching trays, working models from restorative procedures (crown/dentures) and night guards. The British Orthodontic Society also recommends the digitalisation of study models for digital storage using 3D scanners (BOS, 2015).

Though various studies have proposed methods of automation in the recent past, there are no reported studies which presented a fully automated software that would align 3D dental models and / or scans and identify the correct match from a large dataset.

6.2 Design and Structure of the Software:

A new automated software - AutoIDD (Automated Identification from Dental Data) was designed by the PI with the help of a software developer, which uses a combination of techniques including Iterative Closest Point (ICP) and Principal Component Analysis (PCA) for accurate identification using 3D dental models and IOS. The structure of the AutoIDD software for an automated alignment and identification process is shown in Fig. 6.1.

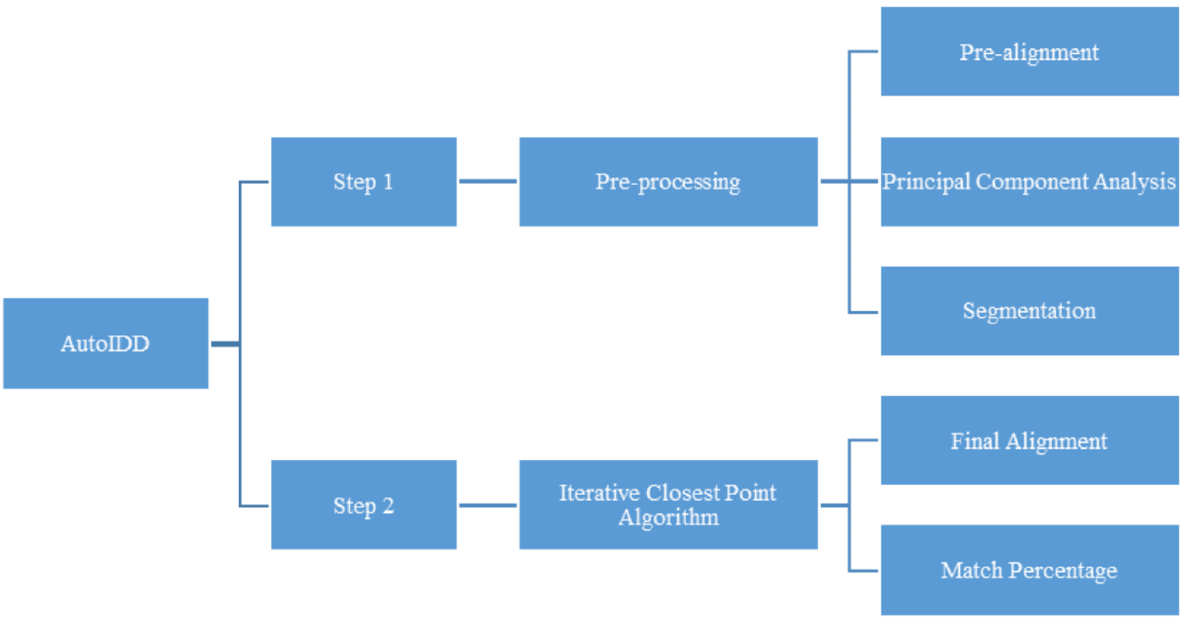


Figure 6.1 The structure and design of the AutoIDD software.

6.2.1 3D Dental Scans - STL files

All the scans require to be in STL format (standard open-source 3D file format). Once imported into 3D compatible software, a STL file is often referred to as a 'mesh'. It is composed of numerous triangles (Fig. 6.2) where each triangle is represented by the (x, y, z) values of each corner. Rather than considering the corners of the triangles, AutoIDD software looks at the centre of each triangle. This is mainly for the benefit of speedy process and for the convenience of having one point per outward normal.

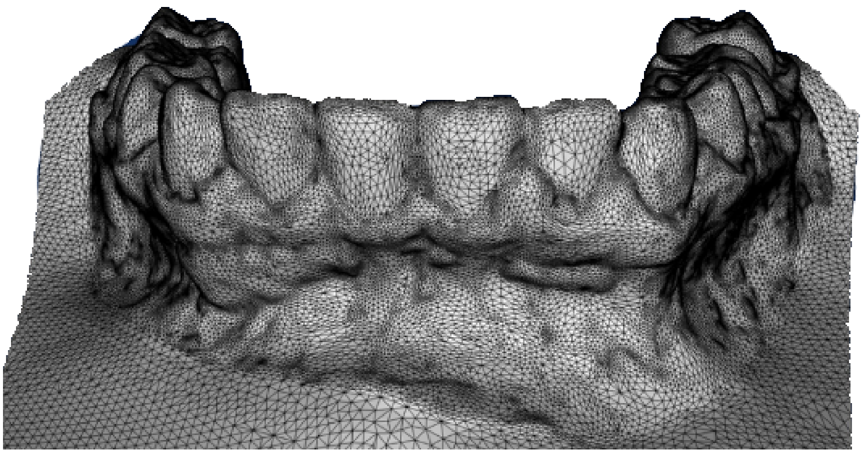


Figure 6.2 3D Mesh of a 3D scanned dental model.

6.2.2 Pre-processing

For an efficient functioning of the ICP algorithm, pre-processing of the 3D scans is required. It is a two-step process which involves the pre-alignment and segmentation/cropping of each of the maxillary and mandibular arches, executed with the help of PCA. The entire collection of the given models can be pre-processed and the output is saved in advance.

6.2.1.1 Pre-alignment

This process is designed to consistently position and orientate any dental scan so that the centre of mass of the model is at the origin.

An overview of the steps involved:

- Use PCA to obtain three basis vectors (x, y, & z).
- Check the signs of each basis vector.
- Fit a plane through all the tips of the teeth to gain a more accurate “up” basis vector.
- Adjust the “forwards” vector to maintain orthogonality with the new “up”.

6.2.1.2 Principle Component Analysis

The most well known approach computing the alignment of 3D objects is the PCA analysis method (Bustos et al., 2004), which is based on the computation of moments of 3D scans. After a translation of the centre of mass to the origin of the coordinate system, three principal axes computed with PCA are used to determine the orientation (Mudrova and Procházka, 2005).

Principal component analysis looks at covariance (spread from the centre of mass) in all directions. It comes out with a set of axes (three perpendicular unit vectors) in order of least to most covariance. The eigenvectors are the axes / directions and the eigenvalues are the covariances in those directions (Chaouch and Verroust-Blondet, 2009).

The goal was to find a method that best aligns any 3D dental scan and will consequently align two similar 3D scans in the same way. The 3D scan has symmetries and it is aligned with particular axes or symmetry planes. So the output of PCA on a dental scan should yield up/down (Z-axis) as the first unit vector, forwards/backwards (Y-axis) as the second and left/right as the third (X-axis). The eigenvectors are unsigned which means the first vector could be either pointing up or down and likewise with the other two.

The dental scan is most detailed on the occlusal surface. The surfaces were compared to the PCA's "Up" according to the dental scan, i.e. maxillary or mandible which is determined by the filename (AM/PM-MaxiSTL, AM/PM-MandSTL) and adjusted if needed. The comparison of unit vectors is completed using the scalar product. The AutoIDD software uses the following basis vectors after a series of computations (Fig. 6.3):

- The "up" (regardless of it being maxillary or mandibular arch) vector of the scan is parallel to the z-axis.
- The "right" (patient's right) vector of the model is parallel to the x-axis.
- "Forwards" is parallel to the y-axis.

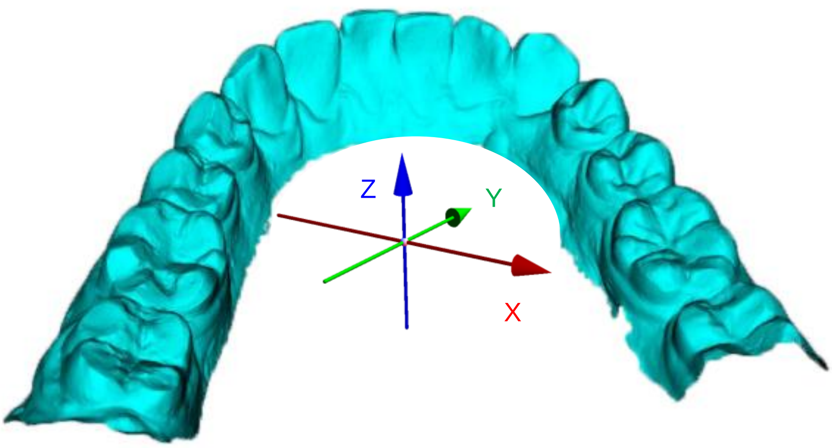


Figure 6.3 Position and orientation of a 3D scan with the PCA vectors.

6.2.1.3 Segmentation

Segmentation, also referred to as cropping is defined as the process of separating the 3D model into segments that are representative of the model shape, calculated by edge detection. The goal of segmentation is to simplify the representation of a model/mesh into something that is more tangible and easier to analyse (He and Wang, 2018). Manual segmentation is very time consuming for large datasets to eliminate the non-dental/ plaster part of the dental model which does not contain information of the teeth. Therefore, many automated (Kronfeld et al., 2010) and semi-automated (Kondo et al., 2004) computer based systems have been developed that can accurately demarcate the desired dental component in the model.

In this software, once the pre-alignment of the model was attained, an automated segmentation plane dissecting the dental cast was executed. In Python™, which is an open source programming language (Python Software Foundation, version 3.8.0, Beaverton, USA), arch meshes can be sampled according to a specific instruction i.e. "to include all points above a certain height". AutoIDD finds the highest point in the direction [0, 1, 1] if mandibular mesh or [0, 1, -1] if maxillary mesh. This point should approximately be the midpoint of the incisal edge. Then the mesh was cropped so that anything more than 9 mm below or 45 mm behind the incisal edge midpoint was eliminated (Fig. 6.4). Additionally the test model was cropped by another 1mm vertically and 3mm horizontally just before the ICP process. This step was to ensure that the test scan includes areas that the reference scan contain and make certain that each point on the test scan is paired with the corresponding point on the reference model.

Standardisation of the methodology is an important element of minimising soft tissue influence and increasing accuracy. Hence, the height and length of the segmentation plane was chosen with the intention to include just the dental components in the scan. These values can be adjusted to obtain a desired plane with a goal to limit the gingival area. The same segmentation procedure was applied to the intra-oral scans.

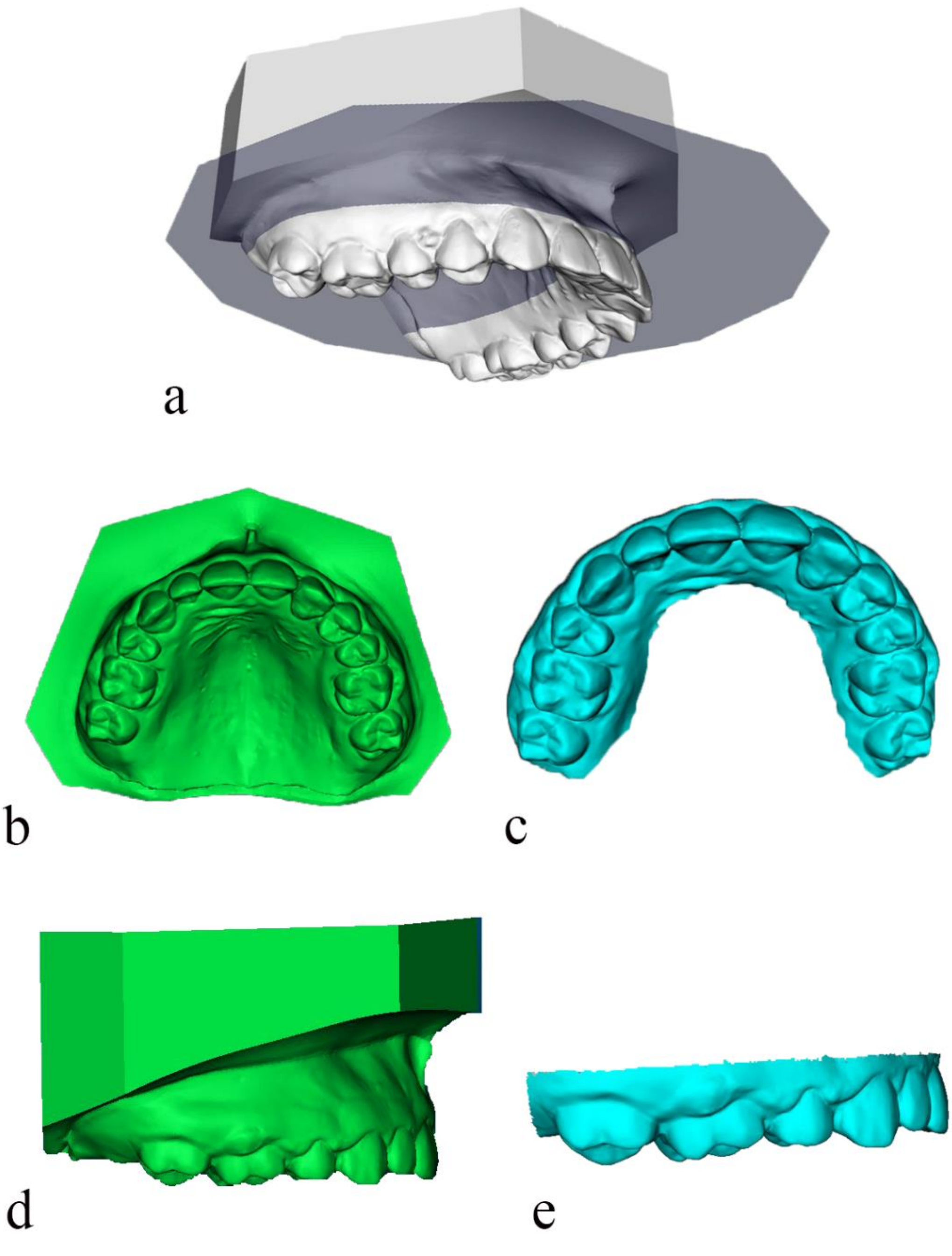


Figure 6.4 Image "a" shows the automated segmentation plane of a 3D dental model; images b, d shows before and c, e after the process of segmentation.

6.2.3 Iterative Closest Point (ICP)

A method for an accurate and computationally efficient registration of 3D shapes was developed based on the ICP algorithm which is to find the closest point on a geometric entity to a given point (Besl and McKay, 1992). The algorithm finds 3D correspondences between two point sets (a reference and a test set) and tries to determine the best match on the “reference” set in terms of minimum distance. This whole process is considered as one iteration and it continues until the alignment of the models is deemed either satisfactory or unlikely to improve.

Another study (He et al., 2017) proposed an ICP algorithm which uses the geometrical features of the point cloud to be be registered, such as curvature, surface normal and point cloud density, to search the correspondence relationship between two point clouds and introduce the geometric features into the error function, to achieve accurate registration of the two point clouds.

Generally, a well matching model pair will converge quickly in 10 - 20 iterations, then improvement rates will rapidly drop. Whereas a poorly matched pair will gradually decline down to a minimum error. To give a good balance between performance and speed, AutoIDD will continue to iterate until the errors cease to improve by at least 0.1% or when the iterations reach 100. The ICP moves the test model in small steps per iteration and will always seek to make an improvement on every iteration. The only way to attain an optimal point is through the process of pre-alignment, which guides the test model to reach the desired position approximately. It is of utmost importance that the plaster base of the dental models and other non-dental features are removed and the meshes are trimmed to consistent measurements. Failure to do so leads to misleadingly high error scores and instability within the ICP.

The ICP is not mathematically stable. An iteration can sometimes worsen the alignment rather than improve it. This is common when the current alignment is very poor and predicting the correspondence based on nearest points is far from accurate. In cases like this the test model will often behave unpredictably, for instance flip upside-down. The solution to avoiding this performance is to ensure that the models were reasonably close to each other when the process starts.

The ICP aims to find the ‘best’ superimposition of a ‘test model’ upon a similar ‘reference model’ where the correspondence between the test points and the reference points is unknown. For an ICP to reliably give satisfactory results, it is required that:

- the models were pre-aligned to attain the most approximate position.
- the models must go through the segmentation process, which is to remove everything below the teeth area and the posterior part of the model as per the desired measurements.
- the test model should undergo an extra cropping stage to ensure that the boundaries of the model are within the reference model.

6.2.4 AutoIDD User-interface:

The AutoIDD software was designed with a user-interface which has four main sections. The digital dental data can be imported into **“Reference section”** (AM) and **“Unknown section”** (PM), see Fig. 6.5. The results will be displayed in the **“Results section”** and a **“viewing section”** for inspection of the 3D scans. This AutoIDD software is compatible on a windows laptop/desktop or mac operating system.

There are two sets of tool bars in the user-interface. The one located below the data import sections contain buttons for initiating commands. Each data import section has a set of buttons for performing the following functions:

a. **Visible button:** Once a scan is imported, a command button with dual function appears for each scan; **“Show” / “Hide”.** The operator can inspect the 3D scan in the viewing section by clicking show or can hide that scan to view another scan.
b. **Colour button:** Using this button the colour of the scan can be changed.
c. **Open:** allows the operator to import the data into that particular section.
d. **Close selected:** closes the selected 3D scan(s).
e. **Close all:** closes all the 3D scans in that particular section.
f. **Hide all:** hides all the 3D scans in that particular section.
g. **Show all:** shows all the 3D scans in that particular section.
h. **Align selected:** aligns the selected set of data.
i. **Align all:** allows the operator to align the entire datasets to produce results.

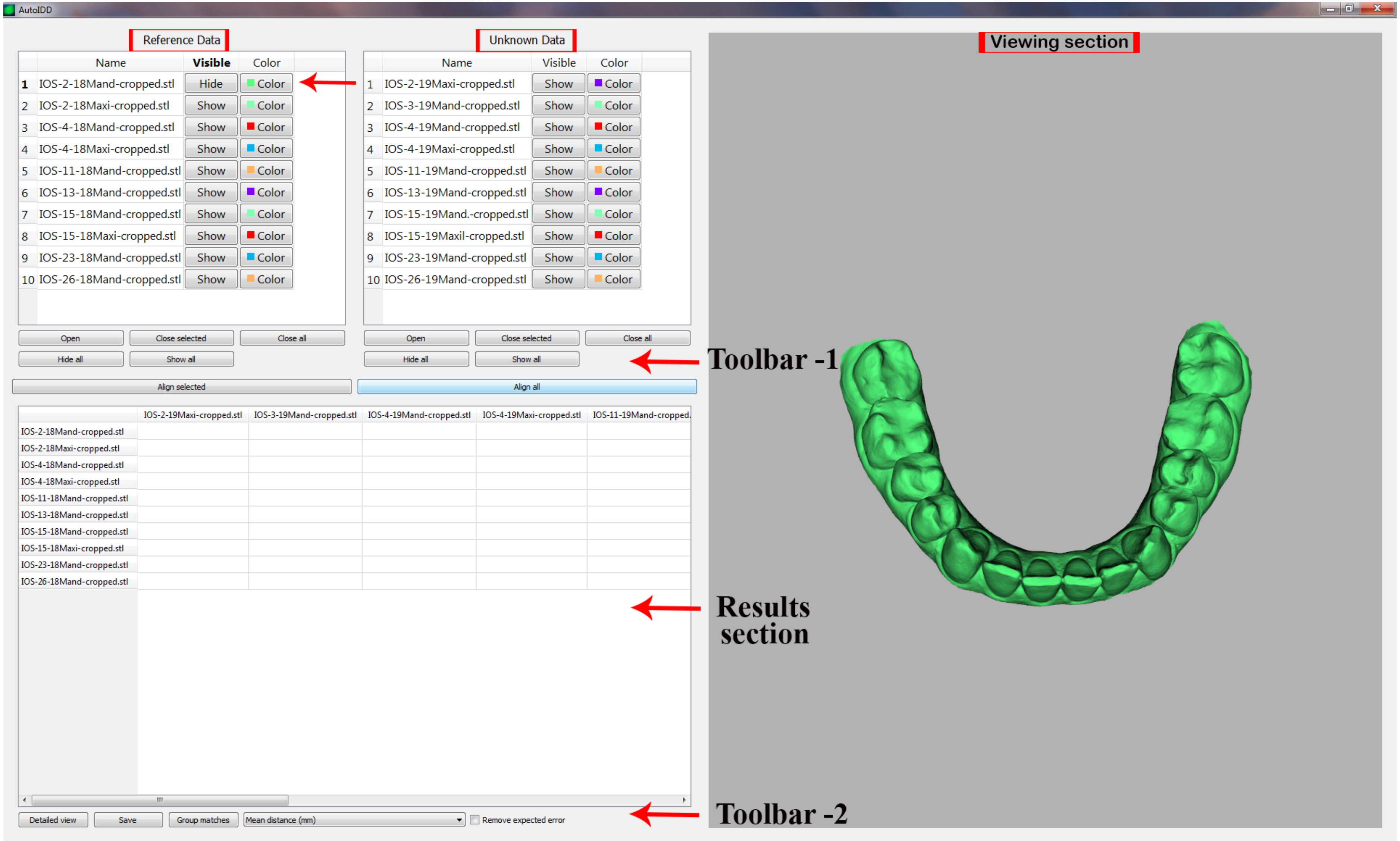


Figure 6.5 shows the User-Interface of the AutoIDD software with the toolbars and function buttons and a 3D dental scan in the viewing section.

The second toolbar is located at the bottom of the results window section which facilitates with the data interpretation. The following buttons and their functions are described below:

a. **Detailed view:** This populates a data table which gives detailed information of that particular 3D pair, see Fig. 6.6 A. This is incorporated with an **"Alignment"** and **"Plot"** buttons, where each generates a colour map of that 3D pair for qualitative and quantitative evaluation respectively. The reference model (AM) is depicted in red while the unknown model (PM) in green for visual differentiation. The alignment button (Fig. 6.6 B) is for qualitative analysis, which shows any discrepancies in the alignment of the 3D arches (in case of a non-match) and the plot button (Fig. 6.6 C) for superimposition (quantitative), to identify the amount of match/non-match areas between that pair. These colour maps can be saved in any preferred orientation as JPEG images.
b. Once the results are produced, a drop-down menu enables the display of the pair-wise results in a preferred interpretation such as match score percentages, mean distances, RMS (root mean square) and standard deviations.
c. The software generates excel sheets to export the results. This can be completed by clicking the **"Save"** button.
d. Expected error: It is the estimated error of a minimum possible mean distance for the reference scan. It helps in the computation of the match percentage.

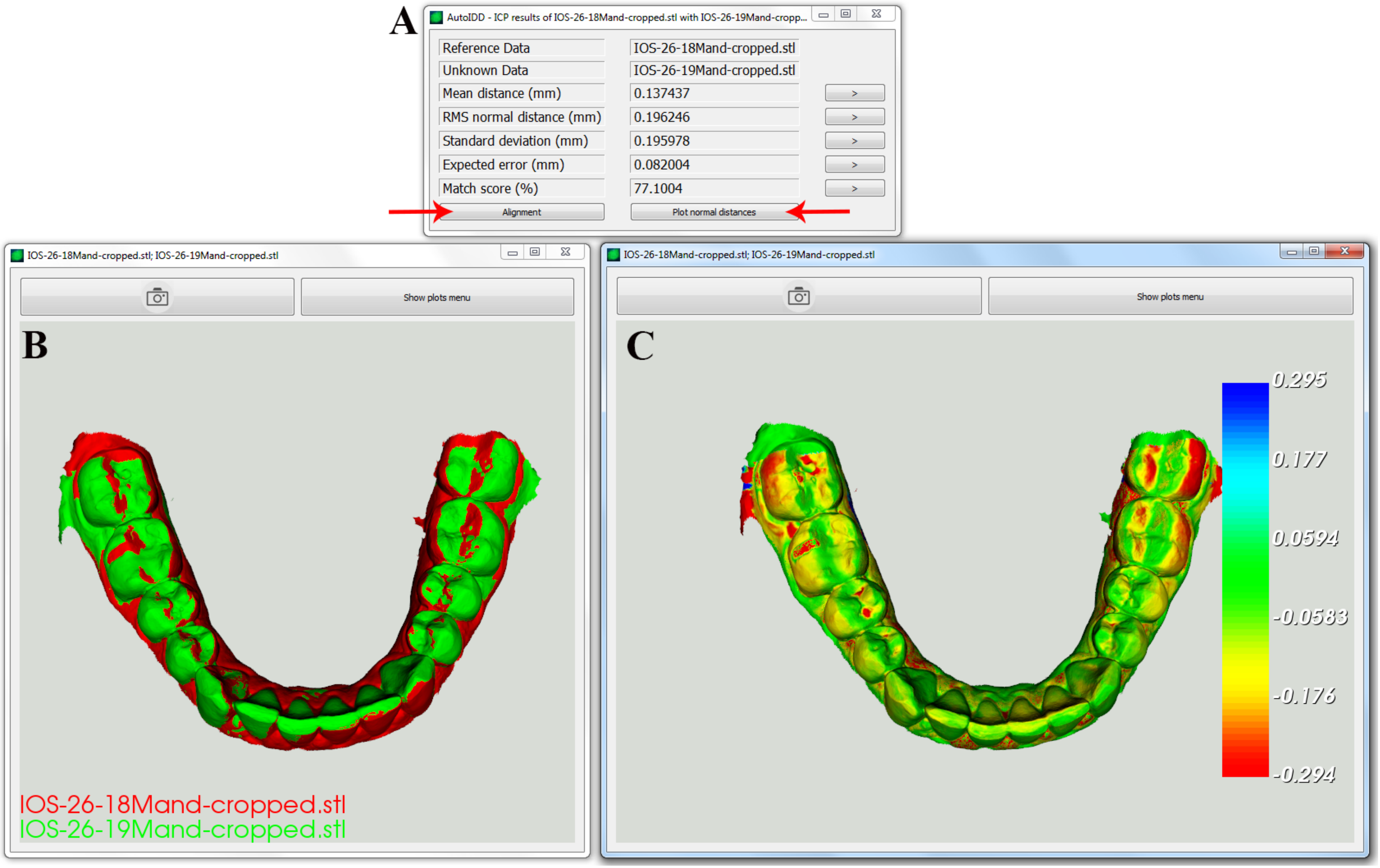


Figure 6.6 shows the detailed view data table and the alignment and plot buttons that enables the inspection of the automated pair-wise alignment and superimposition of 3D scans.

The main purpose of the AutoIDD software is to align and identify matching dental patterns from the reference data. The entire area of both the processed test and reference scans were considered in the automated registration process mainly focussing on the dental components. All the previous studies used existing software which had some limitations. The major advantage of AutoIDD software is that it was designed and developed to be fully automated and no manual intervention is required. It also eliminates the need for surface registration and manual segmentation and there are no specific landmarks involved in the process. Fully automating means that the automated software handles the processes entirely on its own. Aside from the initial set up and the occasional check-in, the software needs no human input to complete the given tasks.

The match percentage is computed by using the mean distance and the expected error. As the AutoIDD software considers the centre of each triangle in the mesh/scan surface, all the points on the “test scan” are compared to the nearest corresponding points on the “reference scan”. The mean of all the point-to-point (minimum) distances were referred to as ‘mean distance’ in the results. Therefore, pairs with least mean distance between the 3D meshes, have a better alignment and superimposition, and a higher probability of being a “positive identification”. This quantitative measure provides an estimate of the similarity between the two models/scans.

The evaluation of the 3D pairs can be performed through the colour maps. Areas with a high degree of match in the arches are shown in green with some shades of yellow. Shades of blue and red represent extreme overlaps.

6.3 Software Testing

An experimental study was conducted to test the accuracy of AutoIDD software within a specific type of dataset.

6.3.1 Data Acquisition

The total test sample consisted of 120 3D maxillary and mandibular dental data. Sixty dental casts of 30 post-orthodontic patients (30 maxillary and 30 mandibular dental models) were collected (Fig.6.7). As a routine procedure, the dental impressions were obtained for patients referred to the Orthodontic clinic, Dundee Dental Hospital, Dundee, Scotland, attending for de-bonding procedures, by the clinician with alginate (Exact Alginate, UnoDent Ltd, UK). The study casts were fabricated on the same day in 100% dental stone (Yellow Stone, John Winter & Co. Ltd., Halifax, UK). According to the clinical data storage protocol, all the patients' dental casts, who had their treatment completed, were laser scanned to create indirect 3D digital images of dental models by the laboratory technicians for digital storage. The dental casts were laser scanned using R700 3Shape Orthodontic Study Model Scanner (Fig. 3.1) (Copenhagen, Denmark) and the images were saved in stereolithography (STL) format. The digitalisation process of the dental casts may generally happen within a week from the fabrication of the study cast. All the patient identifying information was removed and a unique study code was assigned to each 3D dental model by the PI. For the purposes of this study these 3D models were considered as "AM digital data".

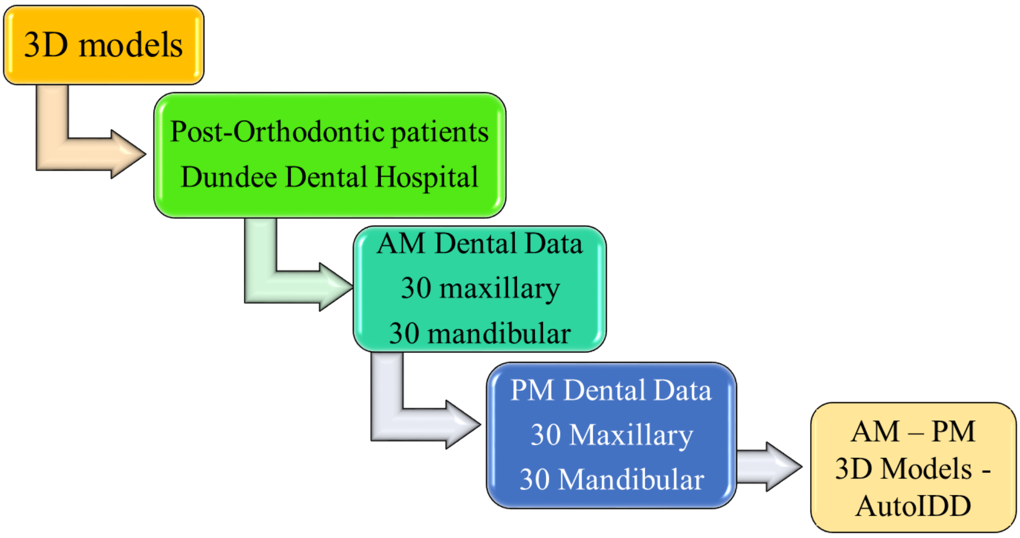


Figure 6.7 Outline of methodology using Test data: Post-Orthodontic Maxillary and Mandibular AM-PM 3D dental models.

To generate an identical sample, 60 dental casts (30 maxillary and 30 mandibular) of the same patients were retrieved and laser scanned by the PI and were considered as "PM digital data". The time lapse between the initial scan by the laboratory technician and the second scan by the PI varied from six months to one year. This test is to determine whether different scans obtained from the same patient's casts were identifiable. The rationale for using the post-orthodontic patients was to make it as difficult as possible for the software by using a sample of patients with similar dentitions. This will help evaluate the performance of the software in identifying the correct 3D dental model matches, representing an AM-PM comparison.

6.3.1.1 Inclusion and Exclusion criteria

Patients who had consented for their records to be used for research purposes were identified through the clinic registry by the principal investigator (PI). Only intact dental casts were included.

6.3.2 Data processing using full arch 3D dental models:

This part of the testing was conducted by using post-orthodontic 3D dental models. Thirty AM and 30 PM maxillary dental models were imported into the "reference" and "unknown" sections of the AutoIDD interface respectively. These were aligned for automated comparison (superimposed) and identification of correct matching pairs.

Additionally, a 3D pair (maxilla and mandible) was selected at random and the occlusal surfaces of the dentition (incisal edges and cusp tips of posterior teeth) were reduced by 2mm. This was to see whether the process of attrition in human dentition; i.e. tooth surface loss, effected the automated identification process.

Once the data was processed, the results were displayed in a tabular form (vertical – reference data; horizontal – unknown / test data) for all the automated alignments. The statistical analysis of the study datasets were assessed using IBM® SPSS Package Version 22 (New York, USA).

6.3.3 Data processing using Partially Edentulous Dental Models:

In this part of the testing, four 3D dental models (two maxillary and two mandibular) were selected at random from the reference (AM) dataset. The corresponding / matching study models were retrieved from the PM dataset, of which six dental arch modifications were prepared. The anterior and posterior teeth (pre-molars and molars) were removed to simulate partially edentulous PM dental arches in a dental identification scenario. These modified / altered study models were laser scanned using R700 3Shape Orthodontic Study Model Scanner (Copenhagen, Denmark) and the images were saved in stereolithography (STL) format. These models were considered as "PM - Modified 3D models".

The modified PM models were processed through the AutoIDD software, as shown in the Figs. 6.8 A-E, for assessing its performance with automated comparison and match percentages.

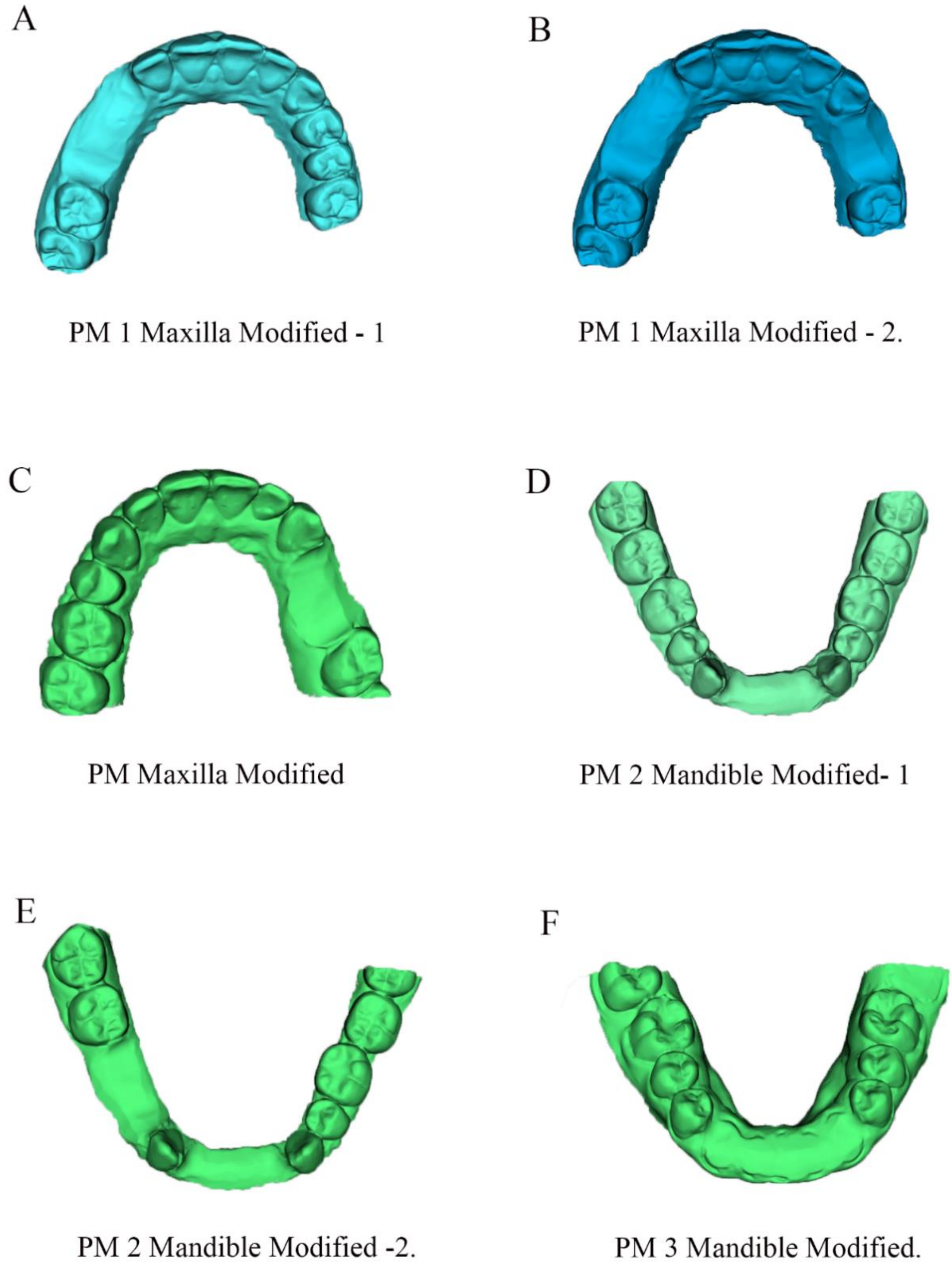


Figure 6.8 Modified PM models – 3D maxillary and mandibular arches.

6.4 Results

6.4.1 Results of Full Arch 3D dental models

The results showed that the AutoIDD software was able to correctly distinguish the matching dental models from the non-matches in all cases. In both the experimental studies (maxillary and mandibular models), all of the matching AM-PM 3D pairs were scored as 100%. This process validates the function of AutoIDD software. The mean distance, standard deviation and RMS of the “correct 3D dental model matches” (maxillary and mandibular) are shown in Table 6.1. A threshold of 0.3 mm of the mean distances was used.

Analysis of the 3D models displayed a total of 900 automated comparisons and alignments (30 AM x 30 PM) for each data set. Every “Unknown” model (PM) aligned with the given “Reference” (AM) models. This resulted in 30 correct matches based on “best fit alignment” and 870 non-matches. The match percentages of the corresponding AM and PM maxillary and mandibular dental models were indicated in green, as shown in Figs. 6.9 & 6.10. The histograms of the distribution of percentages are shown in Figs. 6.11 & 6.12.

Dental Arches	3D scans	AM Data (n)	PM Data (n)	Minimum Match percentage	Maximum Match percentage	Maximum Non-match percentage	Mean Distance (mm) of Correct matches	Mean Distance (mm) of Non-matches	Standard Deviation (mm) of Correct matches	RMS (mm) of Correct matches	RMS (mm) of Non-matches
Maxillary	Dental Models	30	30	-	100	7.7	0.075	0.76	0.006	0.03	1.00
Mandibular	Dental Models	30	30	-	100	8.6	0.076	0.80	0.013	0.06	1.04

Table 6.1 shows the results obtained from the automated comparison of AM-PM 3D Dental Models.

	PM-01Maxil	PM-02Maxil	PM-03Maxil	PM-04Maxil	PM-05Maxil	PM-06Maxil	PM-07Maxil	PM-08Maxil	PM-09Maxil	PM-10Maxil	PM-11Maxil	PM-12Maxil	PM-13Maxil	PM-14Maxil	PM-15Maxil
AM-01Maxil	100	4.01	2.03	2.93	2.81	4.68	2.23	3.27	4.31	3.09	1.88	2.79	2.50	3.38	3.53
AM-02Maxil	3.64	100	2.08	2.62	3.69	3.59	2.73	3.08	3.40	2.71	1.95	2.58	2.05	3.21	3.31
AM-03Maxil	2.28	2.28	100	1.44	2.36	1.94	1.87	1.80	2.68	1.69	1.30	1.70	1.27	1.58	1.57
AM-04Maxil	3.00	2.65	1.54	100	2.71	3.83	3.19	3.51	3.52	3.68	2.78	5.22	3.61	3.72	4.38
AM-05Maxil	3.22	3.64	1.75	2.56	100	3.63	3.01	2.27	3.00	2.77	1.95	2.75	2.16	2.53	3.12
AM-06Maxil	4.40	4.02	1.97	3.56	2.85	100	2.14	4.19	5.31	4.73	1.97	3.61	3.01	4.87	6.26
AM-07Maxil	3.47	2.99	1.90	2.79	3.27	3.40	100	3.41	4.05	2.60	2.51	3.04	2.43	3.13	2.88
AM-08Maxil	2.95	3.80	1.85	3.83	2.79	4.18	2.70	100	4.18	4.68	2.30	3.63	2.76	3.63	4.24
AM-09Maxil	3.15	2.83	2.34	2.31	2.57	3.63	2.07	2.93	100	3.27	1.82	2.45	1.75	2.52	3.02
AM-10Maxil	3.16	3.42	2.03	4.36	3.09	4.43	2.67	4.68	5.01	100	2.75	3.75	3.34	4.18	4.20
AM-11Maxil	2.68	2.36	1.48	3.15	2.21	3.37	2.96	2.87	3.22	3.37	100	3.22	6.09	3.52	3.78
AM-12Maxil	2.55	2.75	1.53	5.57	3.01	3.41	3.09	3.48	3.42	3.67	3.06	100	3.35	5.62	3.94
AM-13Maxil	2.62	2.38	1.43	3.91	2.29	3.26	2.81	2.85	3.21	3.21	4.09	3.47	100	3.54	3.91
AM-14Maxil	3.20	3.23	1.61	4.27	3.56	4.92	3.06	3.61	3.75	4.43	2.81	5.77	3.51	100	5.17
AM-15Maxil	3.78	3.55	1.61	4.54	2.47	6.12	3.08	3.84	3.51	3.87	2.89	3.96	3.59	4.97	100
AM-16Maxil	2.71	2.68	1.69	2.69	2.83	3.29	2.69	3.44	3.64	3.46	2.72	4.60	2.78	3.48	3.27
AM-17Maxil	2.86	3.00	1.75	4.62	3.39	3.50	2.00	2.76	3.88	4.05	2.55	6.32	3.14	5.33	3.57
AM-18Maxil	2.66	2.37	1.53	4.35	2.38	4.09	3.28	3.38	3.63	4.18	3.30	5.49	3.88	5.67	4.53
AM-19Maxil	2.72	2.76	2.00	3.45	2.78	4.18	2.61	3.34	4.07	5.38	2.72	3.86	3.70	3.79	3.93
AM-20Maxil	3.07	3.11	1.80	4.62	3.10	4.30	2.88	4.78	4.01	5.52	2.96	3.99	4.33	4.74	4.58
AM-21Maxil	3.80	4.56	2.34	2.88	3.57	5.05	2.48	3.79	4.61	3.68	1.92	3.33	2.30	3.67	3.80
AM-22Maxil	2.80	2.72	1.67	5.03	2.86	3.57	3.47	3.23	3.36	3.25	3.09	5.04	3.26	3.65	3.96
AM-23Maxil	3.14	4.01	2.01	3.35	3.52	4.99	3.01	4.57	3.97	4.14	2.50	5.23	2.62	5.42	4.51
AM-24Maxil	2.93	2.80	1.70	3.42	2.77	4.26	2.51	3.18	4.17	4.19	2.46	4.20	3.66	4.21	4.01
AM-25Maxil	4.02	3.17	2.59	2.64	2.40	3.65	1.38	2.61	3.45	2.61	1.40	2.67	1.95	3.43	2.83
AM-26Maxil	3.21	3.21	1.46	4.53	2.55	4.98	2.32	3.34	3.51	4.08	3.55	5.03	4.85	6.61	6.05
AM-27Maxil	3.37	3.81	1.95	3.44	3.20	4.89	2.30	3.59	4.04	4.07	2.32	4.32	3.15	5.99	4.67
AM-28Maxil	3.36	3.16	1.99	3.68	3.49	5.27	3.03	3.70	4.53	5.34	2.85	4.20	3.15	4.49	4.03
AM-29Maxil	2.53	3.09	2.27	2.83	3.72	4.01	2.95	2.97	3.91	3.39	2.43	3.54	2.48	3.10	2.64
AM-30Maxil	2.33	2.10	1.26	4.14	2.19	2.67	2.85	2.56	2.92	2.93	3.39	3.04	4.74	3.48	3.14

	PM-16Maxil	PM-17Maxil	PM-18Maxil	PM-19Maxil	PM-20Maxil	PM-21Maxil	PM-22Maxil	PM-23Maxil	PM-24Maxil	PM-25Maxil	PM-26Maxil	PM-27Maxil	PM-28Maxil	PM-29Maxil	PM-30Maxil
AM-01Maxil	2.68	2.87	2.78	2.73	3.01	4.76	2.39	4.00	2.76	2.98	3.46	3.99	3.83	2.39	1.75
AM-02Maxil	2.38	2.88	2.38	2.31	2.87	4.82	2.08	3.61	2.43	3.01	2.96	3.87	2.86	2.59	1.74
AM-03Maxil	1.67	1.73	1.50	1.64	1.50	2.33	1.47	2.14	1.68	1.48	1.58	2.06	2.07	2.02	1.02
AM-04Maxil	3.53	4.67	4.69	3.44	4.28	3.11	4.36	3.62	3.44	2.59	4.43	3.71	3.44	2.71	2.31
AM-05Maxil	2.41	2.93	1.99	2.49	3.44	3.68	1.93	2.64	2.58	1.71	3.13	3.88	3.13	2.35	1.65
AM-06Maxil	3.27	3.65	4.12	4.13	4.17	5.24	2.84	4.88	4.12	2.55	5.12	5.13	3.10	2.91	2.03
AM-07Maxil	2.71	2.85	2.86	2.64	2.50	3.10	2.84	4.20	2.70	2.25	3.10	3.68	4.19	2.72	1.57
AM-08Maxil	3.63	3.80	3.68	3.44	4.54	4.05	3.01	4.39	3.42	2.75	3.56	3.75	3.83	3.05	2.07
AM-09Maxil	2.58	2.44	2.49	2.95	2.35	3.34	2.14	3.84	2.92	2.13	2.21	3.08	2.86	2.89	1.33
AM-10Maxil	3.56	4.15	5.18	5.83	5.48	4.05	3.48	3.96	4.55	3.08	4.37	4.19	5.36	3.35	2.05
AM-11Maxil	2.91	2.87	4.21	3.64	3.94	2.80	3.42	3.10	4.28	2.85	3.88	3.02	3.27	2.62	2.95
AM-12Maxil	4.59	6.60	5.42	4.10	3.84	3.35	4.64	5.05	4.16	2.64	4.90	4.25	3.72	3.14	2.31
AM-13Maxil	2.79	3.03	4.23	3.80	4.24	2.82	3.11	2.78	4.33	2.14	4.35	3.48	3.15	2.24	3.38
AM-14Maxil	3.64	5.65	6.33	4.34	4.51	3.89	3.02	5.35	4.30	3.03	6.39	6.81	4.38	3.13	2.86
AM-15Maxil	3.14	3.56	4.72	3.79	4.33	3.93	2.94	3.84	4.11	2.84	5.72	4.66	3.87	2.66	2.27
AM-16Maxil	100	4.45	3.02	3.10	3.23	2.98	4.08	4.26	3.46	2.28	3.32	3.52	3.59	3.48	1.90
AM-17Maxil	4.59	100	4.76	4.03	3.93	3.79	2.83	5.27	3.80	2.90	4.15	5.07	3.78	3.68	3.12
AM-18Maxil	3.29	4.72	100	4.17	4.03	3.33	4.18	4.37	4.67	2.85	5.38	4.39	4.27	2.63	3.86
AM-19Maxil	3.18	4.02	4.22	100	3.58	3.22	3.32	3.66	7.69	2.02	4.14	4.09	3.89	3.10	2.13
AM-20Maxil	3.43	4.41	5.06	4.00	100	4.33	2.79	3.90	3.83	3.17	5.56	4.43	5.32	2.81	2.70
AM-21Maxil	2.91	3.54	3.02	3.09	3.41	100	2.32	5.81	3.22	2.82	3.43	4.83	4.26	3.02	1.61
AM-22Maxil	4.53	4.61	4.29	3.87	3.49	2.93	100	4.12	4.12	2.59	4.12	3.52	3.48	3.01	2.54
AM-23Maxil	4.21	5.27	4.28	3.71	3.97	5.68	3.74	100	4.08	2.75	4.74	5.19	4.65	3.67	1.91
AM-24Maxil	3.55	3.86	4.22	7.09	3.77	3.48	3.56	3.87	100	1.98	4.13	4.22	4.16	2.91	2.08
AM-25Maxil	2.15	2.95	2.91	2.22	3.44	5.27	1.81	3.29	2.30	100	2.71	3.24	2.58	2.03	2.41
AM-26Maxil	3.32	4.17	6.10	4.13	5.11	3.52	3.22	4.51	4.54	2.90	100	5.64	2.66	2.59	2.60
AM-27Maxil	3.26	4.85	4.09	3.88	3.72	4.90	2.87	4.88	4.14	2.54	4.89	100	3.90	3.63	1.91
AM-28Maxil	3.79	4.21	4.73	4.27	5.32	4.93	3.24	5.12	4.46	1.99	4.50	4.57	100	3.34	1.88
AM-29Maxil	3.68	3.98	3.02	3.35	2.75	3.30	2.91	3.81	3.57	2.12	3.00	3.99	3.71	100	1.68
AM-30Maxil	2.34	2.44	5.72	3.20	3.17	2.09	3.42	2.57	3.65	2.58	4.03	2.83	2.87	1.79	100

Figure 6.9 Match percentages of AM – PM maxillary dental models. The correct matching pairs are indicated in green and the maximum non-match percentage is shown in blue.

	PM-01Mand	PM-02Mand	PM-03Mand	PM-04Mand	PM-05Mand	PM-06Mand	PM-07Mand	PM-08Mand	PM-09Mand	PM-10Mand	PM-11Mand	PM-12Mand	PM-13Mand	PM-14Mand	PM-15Mand
AM-01Mand-	100	2.35	2.19	2.87	2.04	3.65	2.51	2.63	2.47	2.87	2.52	3.40	2.75	4.09	2.76
AM-02Mand-	2.41	100	3.32	3.32	2.51	2.43	2.89	3.69	2.04	2.44	2.47	3.16	1.84	3.32	2.44
AM-03Mand-	2.37	1.20	100	2.46	3.23	2.60	3.76	2.32	1.76	2.81	1.84	2.59	1.84	2.98	2.30
AM-04Mand-	2.97	3.41	3.33	100	2.94	3.55	3.60	3.38	2.54	4.17	2.98	5.54	2.58	4.84	3.50
AM-05Mand-	2.46	1.04	3.89	2.36	100	2.42	2.97	2.13	1.70	2.16	1.88	2.71	1.94	3.15	2.29
AM-06Mand-	4.41	3.14	2.66	3.73	2.50	100	3.49	3.81	2.90	3.51	3.36	5.59	3.64	6.02	4.13
AM-07Mand-	2.80	3.07	4.24	3.66	2.94	3.46	100	3.65	2.32	3.32	2.64	3.69	2.55	3.50	3.50
AM-08Mand-	2.60	3.24	2.69	3.03	2.08	3.55	2.93	100	3.06	3.04	2.32	3.49	2.22	3.97	2.94
AM-09Mand-	1.84	1.90	1.43	1.84	1.54	2.07	1.72	2.23	100	2.22	2.40	2.21	1.91	2.27	2.42
AM-10Mand-	3.01	2.05	2.62	4.17	2.01	3.69	3.38	3.17	3.03	100	3.34	3.98	3.60	3.77	4.41
AM-11Mand-	2.50	1.67	2.29	3.40	2.19	3.22	2.70	2.40	3.22	3.73	100	3.02	3.28	3.38	3.67
AM-12Mand-	3.78	3.61	2.98	4.90	2.66	5.33	3.29	3.91	2.90	4.16	3.34	100	3.03	8.66	3.97
AM-13Mand-	3.22	1.42	1.88	2.52	1.90	3.56	2.51	2.38	3.14	3.50	2.89	2.80	100	3.13	4.09
AM-14Mand-	3.69	3.46	2.87	4.73	1.74	4.75	3.04	3.93	2.37	4.08	2.74	5.29	2.32	100	2.61
AM-15Mand-	2.29	2.26	1.88	2.83	1.64	3.02	2.66	2.15	2.82	2.85	2.64	2.72	2.97	2.91	100
AM-16Mand-	2.01	2.83	2.83	2.82	2.56	2.14	2.52	2.60	1.92	2.40	2.20	2.97	1.82	2.60	2.61
AM-17Mand-	2.78	1.62	2.41	3.18	2.16	3.69	2.65	3.17	2.58	4.61	2.96	5.60	2.90	4.99	3.38
AM-18Mand-	3.74	2.39	2.47	3.71	2.34	5.66	3.35	3.27	2.92	4.87	3.54	6.10	4.34	6.48	4.32
AM-19Mand-	3.27	2.74	2.46	3.94	2.44	4.27	2.82	2.93	2.74	3.40	3.16	4.76	3.25	4.47	3.46
AM-20Mand-	2.60	2.75	1.96	3.04	1.97	3.30	1.82	2.56	3.40	3.74	4.17	3.56	2.38	3.61	3.43
AM-21Mand-	2.93	2.53	2.61	3.03	2.63	4.27	2.90	3.34	2.92	4.30	3.28	5.59	3.34	5.65	3.98
AM-22Mand-	2.82	3.14	4.04	3.90	3.24	3.42	4.09	3.18	2.51	3.55	3.25	5.07	2.67	4.43	3.25
AM-23Mand-	2.32	3.33	3.78	3.46	2.29	3.33	3.18	4.62	2.18	3.21	2.28	3.62	2.08	3.99	3.10
AM-24Mand-	3.23	3.28	2.43	3.93	2.32	5.60	3.45	3.16	3.36	4.51	4.01	5.73	3.36	5.57	4.82
AM-25Mand-	3.85	3.56	2.37	3.70	2.79	4.19	2.81	3.11	3.68	3.26	3.93	4.36	3.01	3.69	3.41
AM-26Mand-	3.70	2.98	3.42	3.33	2.76	4.83	4.42	3.83	3.14	4.44	3.03	4.64	3.10	4.23	4.20
AM-27Mand-	2.07	2.67	1.93	3.45	1.88	3.29	2.40	2.90	3.51	4.17	4.35	3.87	3.69	2.82	3.81
AM-28Mand-	3.54	2.45	2.25	3.68	2.31	5.05	2.82	2.65	3.19	3.75	3.56	4.81	3.79	4.63	4.07
AM-29Mand-	2.87	2.78	4.11	2.80	3.00	3.43	4.03	2.81	2.09	2.98	2.42	3.49	2.36	3.31	3.00
AM-30Mand-	2.31	3.09	2.37	4.13	2.13	2.57	2.92	2.90	2.89	4.44	3.42	4.82	2.90	2.78	3.69

	PM-16Mand	PM-17Mand	PM-18Mand	PM-19Mand	PM-20Mand	PM-21Mand	PM-22Mand	PM-23Mand	PM-24Mand	PM-25Mand	PM-26Mand	PM-27Mand	PM-28Mand	PM-29Mand	PM-30Mand-
AM-01Mand-	1.73	2.77	3.73	3.04	2.21	2.82	2.53	2.53	3.24	3.28	2.42	2.30	3.03	2.90	1.95
AM-02Mand-	2.48	2.11	2.73	2.65	2.21	2.58	2.45	4.75	2.89	2.69	2.27	2.10	2.45	3.03	2.13
AM-03Mand-	2.38	2.66	2.80	2.52	1.65	2.40	3.39	3.92	2.24	2.03	3.70	1.40	2.07	4.45	0.87
AM-04Mand-	1.85	3.43	4.73	5.26	2.95	4.42	3.15	3.96	3.64	3.19	4.11	2.86	3.66	3.74	2.21
AM-05Mand-	2.41	2.13	2.73	2.74	1.73	2.53	3.09	3.35	2.07	2.37	2.79	1.53	2.19	3.68	1.44
AM-06Mand-	2.30	3.88	7.17	4.88	3.42	4.75	3.32	3.54	6.39	3.84	4.72	3.63	4.86	3.88	2.05
AM-07Mand-	2.94	2.59	3.82	3.43	2.01	2.72	3.92	4.04	3.16	3.12	4.68	2.10	2.48	4.61	1.80
AM-08Mand-	1.98	3.23	3.15	2.67	2.21	2.98	2.83	4.71	2.95	2.48	3.17	2.34	2.54	2.65	1.81
AM-09Mand-	1.60	2.22	2.24	2.21	2.40	2.26	1.73	1.77	2.52	2.10	1.92	2.47	2.35	1.78	1.85
AM-10Mand-	2.57	3.46	5.46	3.84	3.35	3.17	3.36	3.08	4.52	2.90	4.10	3.76	2.80	3.05	2.05
AM-11Mand-	2.07	3.35	3.73	3.36	3.64	3.17	2.98	2.37	3.45	3.30	3.31	3.30	3.36	2.65	2.07
AM-12Mand-	2.77	5.34	6.88	5.38	3.88	5.60	4.50	4.01	5.44	3.84	4.61	3.78	4.94	3.88	2.35
AM-13Mand-	1.74	2.86	4.23	3.54	2.71	3.21	2.61	2.19	3.82	2.54	2.57	3.31	3.13	2.64	1.94
AM-14Mand-	1.75	4.33	5.97	3.48	2.43	2.95	3.31	4.30	4.02	3.25	2.17	2.29	2.85	3.01	1.82
AM-15Mand-	2.01	3.11	3.22	2.57	2.39	2.97	2.50	2.57	3.49	2.46	2.96	2.91	2.83	2.24	1.92
AM-16Mand-	100	2.12	2.55	2.80	2.14	2.30	2.82	3.56	2.38	2.33	2.29	2.07	1.88	3.26	1.94
AM-17Mand-	2.94	100	5.31	3.51	2.58	4.69	3.35	3.53	4.50	2.71	3.50	2.34	3.95	2.90	1.71
AM-18Mand-	2.37	4.82	100	5.13	3.47	6.07	3.52	3.29	5.75	3.50	4.88	3.86	5.05	3.51	1.91
AM-19Mand-	2.45	3.26	5.04	100	3.54	4.03	2.97	3.14	3.98	3.30	4.24	3.40	3.86	3.55	1.94
AM-20Mand-	1.43	3.02	4.01	4.18	100	3.42	2.28	2.55	3.93	3.42	3.36	2.71	3.56	2.52	2.92
AM-21Mand-	2.42	4.48	6.82	4.68	2.93	100	3.53	3.21	5.17	2.73	4.27	3.02	4.55	3.05	2.15
AM-22Mand-	3.21	3.89	4.14	3.39	2.74	3.57	100	3.66	4.08	3.46	3.94	2.58	3.33	3.86	1.99
AM-23Mand-	2.36	3.40	3.30	2.85	2.09	2.64	3.31	100	2.83	2.54	2.81	2.17	2.50	3.91	2.00
AM-24Mand-	2.43	4.51	6.74	4.66	3.94	5.37	3.79	3.12	100	3.81	3.94	4.39	4.32	3.45	2.58
AM-25Mand-	2.40	3.13	4.36	4.06	3.89	3.41	3.11	2.97	4.59	100	3.07	3.60	4.20	3.32	2.47
AM-26Mand-	2.69	3.39	5.24	4.62	2.64	3.48	3.77	4.40	4.32	3.34	100	2.75	3.61	5.18	1.64
AM-27Mand-	2.18	2.72	4.65	4.22	4.77	4.39	2.52	2.64	4.39	3.04	3.12	100	3.73	2.53	2.74
AM-28Mand-	2.11	4.22	6.16	4.22	3.78	5.32	2.99	2.57	5.09	3.59	3.70	3.53	100	2.98	2.12
AM-29Mand-	2.99	2.36	3.67	3.60	2.05	2.72	3.82	3.84	3.03	2.77	4.97	2.21	2.61	100	1.84
AM-30Mand-	2.38	2.33	3.63	3.85	3.35	2.86	2.79	2.86	3.66	2.91	2.50	4.54	2.50	2.77	100

Figure 6.10 Match percentages of AM – PM mandibular dental models. The correct matching pairs are indicated in green and the maximum non-match percentage is shown in blue.

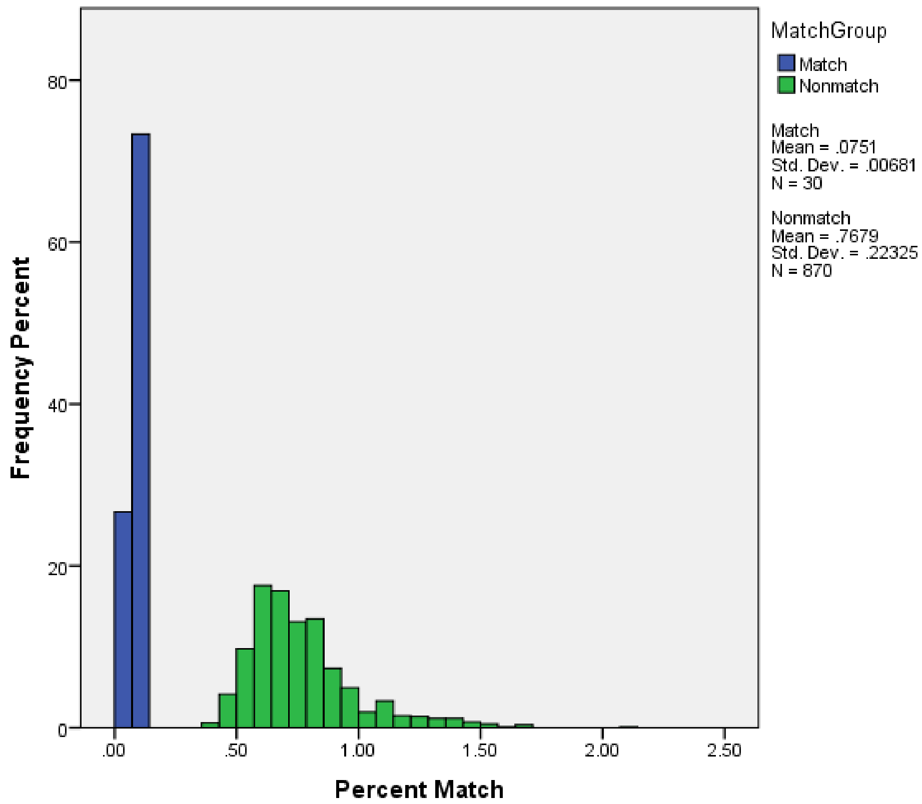


Figure 6.11 Histogram of the distribution of percentage of matches and non-matches of maxillary dental models.

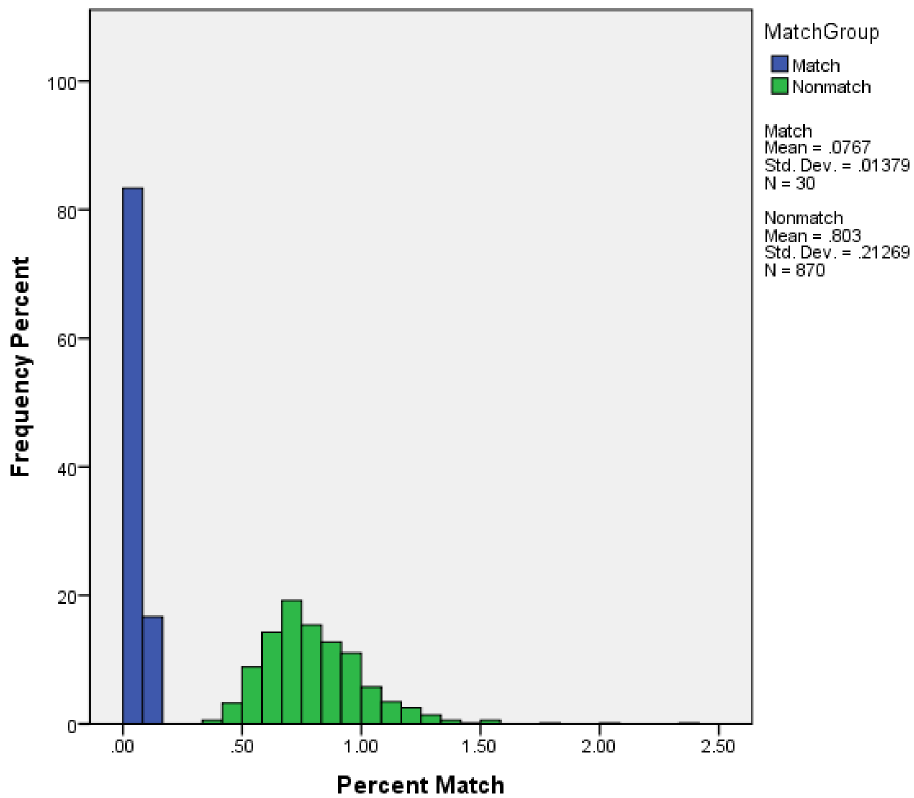


Figure 6.12 Histogram of the distribution of percentage of matches and non-matches of mandibular dental models.

It was also observed that the tooth surface loss (attrition) of 2 mm did not majorly affect the identification process of the software. The corresponding attrited PM 3D pair was identified correctly but with a reduced match percentage; AM-PM maxillary model - 96 % and AM-PM mandibular pair – 91.5 % (Fig. 6.13).

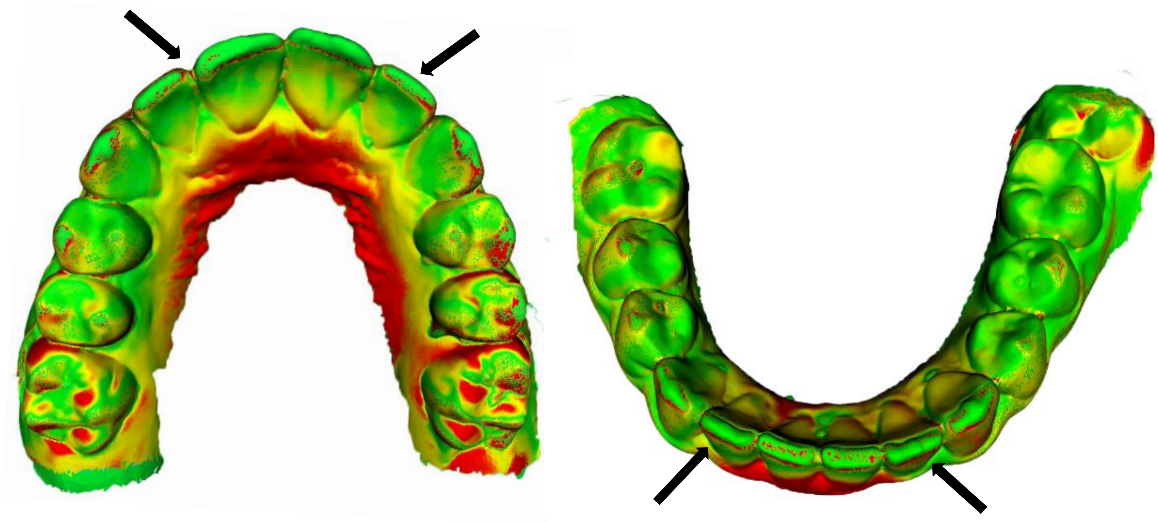


Figure 6.13 Superimposed AM-PM (attrited) 3D models. The attrited surfaces of the 3D scans are indicated by arrows.

6.4.2 Results of the Partially Edentulous 3D models:

The results of this experiment indicate that the AutoIDD software was able to correctly identify the matching modified PM models in only four out of six modifications. Two were falsely identified (AM-1 – PM 1 Modified 1 & 2).

On analysis of the data it was observed that the match percentages of correct AM-PM 3D pairs was reduced and ranged from 7.9 % to 51 %. The least match percentage (7.9 %) was for the model with least number of teeth present (see Fig. 6.8 E) or more number of missing teeth in the arch, while the highest (51 %) was for the model with more number of teeth present or less number of missing teeth in that arch (see Fig. 6.8 C).

The superimposition images of the AM and PM (modified) models with least and highest percentages are shown in Fig. 6.14 A & B respectively while the results are shown in Fig. 6.15.

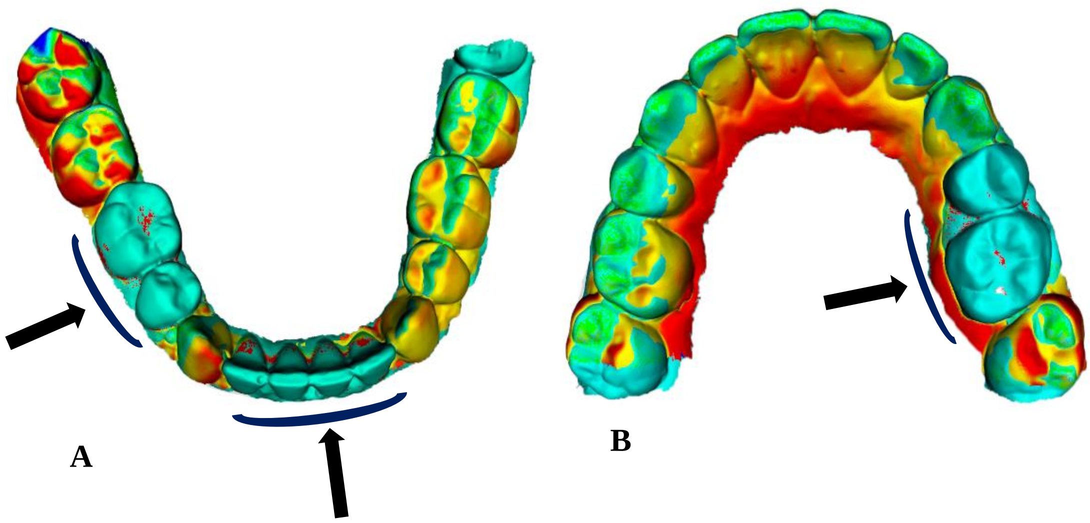


Figure 6.14 The missing teeth in the partially edentulous arch are indicated by arrows.

	PM 1 Maxi Mod 1	PM 1 Maxi Mod 2	PM 2 Maxi Mod	PM 2 Mand Mod 1	PM 2 Mand Mod 2	PM 3 Mod Mand
AM-1 Maxill	3.62%	3.36%	4.02%	0.49%	1.08%	0.35%
AM-2 Maxill	3.28%	2.47%	51.03%	0.69%	0.36%	0.72%
AM-2 Mand-	0.93%	0.69%	0.69%	48.16%	7.94%	2.44%
AM-3 Mand-	0.91%	0.93%	1.18%	2.56%	1.91%	47.78%

Figure 6.15 Match percentages of AM - PM (mod: modified) models. The correct matching pairs are indicated in green.

6.5 Discussion

Superimposition based 3D software such as Vectra-3D, GOM Inspect and Geomagic have been utilised for dental research and evaluation studies. Most of this software are premium products and claims to have automated features for 3D comparison and analysis. A free version of GOM Inspect was evaluated by the PI for its automated features and performance with multiple 3D datasets (Refer Chapter 5 for study details). It was found that the software was unable to perform an automated identification when provided with multiple 3D datasets, however, pair-wise comparison was only possible. It also requires manual intervention and there are no other quantitative features that indicate or identify the correct superimposition to the operator apart from the surface comparison measurements. The conclusions were based on the visual inspection of the 3D pair. In contrast, AutoIDD software efficiently identified the correct matching 3D pairs from large datasets and generates quantitative results for analysis.

A study (Zhong et al., 2013) presented an algorithm for automatic matching using scanned mandibular 3D models. The study was based on feature extraction and description points from the models and concluded that the accuracy was highest with manual-segmented models than auto-segmented PM models. Gibelli et al. also proposed 3D-3D superimposition procedures, where one study analysed anatomical differences between dental elements using the first and second molars (Gibelli et al., 2019b) and another aimed at verifying the uniqueness of 3D models of the palatal rugae (Gibelli et al., 2018). These methods require manual segmentation of the region of interest and surface registration, the least point-to-point distance between the two superimposed surfaces was expressed as RMS. However, AutoIDD software surpasses this by different methods of approach (mean of all the least point-to-point distances of the entire scan and the RMS of the values were also generated by the software so that positive and negative values do not cancel to give a misleadingly low error) and also with several standard deviations between the lowest non-match error and the highest match error.

From the results of the processed full arch 3D dental models, it was observed that the orthodontic treatment increased the similarity and reduced the uniqueness of the human anterior dentition between different patients. These similarities may cause the dentitions to be less distinguishable than before treatment (Dyke et al., 2018). The experimental study data used were all 3D dental models of post-orthodontic treated patients. The results of the test study indicate that the software has correctly distinguished the matching dental models from the non-matches and all the models were found to be a 100% match. This also shows that there were no changes detected in the AM-PM matching pairs. No false positives were observed. This part of the study validated the accuracy of AutoIDD software.

The ICP may also fail when the dentition or teeth are not distributed evenly in the model (more teeth on one side than the other), referred as partially edentulous. The results of the testing with partially edentulous models indicate that the match percentage of the correct matching pairs will either reduce drastically or may be falsely identified. A possible explanation could be due to the variations of the Z and Y axes orientation which are in turn caused by the increased number of missing teeth and non-uniform distribution of the teeth present. The Z-axis of the model can be fixed but the orientation of the Y-axis varies (see, Fig. 6.6). In a few models the error in the Y-axis is sufficient to prevent the ICP from performing as intended. The software was unable to recognise the target dental pattern (partially edentulous - PM) from the reference data (AM) which may have had a full arch pattern.

This chapter presents the design and development of a new automated software named AutoIDD which can process large datasets of 3D dental models. This software was tested using full arch post-orthodontic 3D dental models to determine the performance of the software in identifying the correct 3D dental model matching pairs which were obtained from the same patient. The testing was successful as the target scans were accurately identified from a large dataset with similar dental patterns.

Another part of the testing was conducted using partially edentulous models to assess the stability of the software when provided with dental patterns that present with a non-uniform distribution of teeth. The software struggled with these patterns and so far this stands out to be the only limitation of the AutoIDD software. Further research is required with studies using partially edentulous samples.

The AutoIDD software may further be applied in determining the accuracy and sensitivity of prospective samples.

6.6 Conclusion

The AutoIDD software is unique from the previously mentioned studies and proposed software. The target scan in a large dataset was efficiently identified without any false positives. It also eliminates the need for surface registration and manual segmentation and there are no specific landmarks involved in the process. The availability of AM 3D data has potential to allow for digital comparison with the PM 3D data which can be applied in dental identification cases.

Chapter 7 - Automated Identification from Dental Data (AutoIDD) – Towards a Forensic Application

7.1 Introduction

The application of 3D imaging in dentistry has widely expanded in recent years. As a result, clinical practices and laboratory techniques are shifting to digital workflows (Fasbinder, 2010). The introduction of intra-oral scanners for direct digitalisation of the patient's dental arches were developed as an alternative to the use of conventional impression materials (Naidu and Freer, 2013, Ting-Shu and Jian, 2015). This digital system has important advantages in reducing impression time, patient burden, efficient storage and retrieval, higher accuracy, rapid access to 3D diagnostic information, and easy transferability of digital data (Chalmers et al., 2016, Wesemann et al., 2017).

A feasible and an efficient automated 3D dental identification system would enhance the identification process. This chapter introduces a newly developed automated software - AutoIDD (see Chapter 6 for details of its development) to explore its potential for use by a forensic odontologist in accurately identifying the correct dentition of deceased individuals from the available AM dental records. The objective was to evaluate the functionality of the AutoIDD software using 3D intra-oral scans (IOS) data from a prospective sample for validity and reliability.

A time interval between the collection of two IOS per patient would represent the potential difference between AM records and PM records in a forensic case. This chapter presents two studies that will test the ability of the software to identify / exclude cases despite, a) minor changes in the dentition over the period of a year, and b) major alignment changes in a cohort of orthodontic patients.

7.2 Materials and Method

7.2.1 Data Acquisition

The total study sample consisted of 120 3D maxillary and mandibular dental data (Fig. 7.1). The dental school staff and students were invited to participate in this research, and 30 participants were recruited. To reconstruct a dental identification scenario, 30 maxillary and 30 mandibular dental arches scans were obtained using 3Shape TRIOS Intra-oral Scanner (Fig. 7.2) (Copenhagen, Denmark) by the PI and were considered as IOS-AM. After one year, another set of IOS (60) were acquired from the same participants and were considered as IOS-PM. The purpose of this process was to determine the sensitivity of AutoIDD software towards any subtle variations in an individual's dentition; alignment, morphological and restorative features.

On examination of the maxillary and mandibular AM and PM 3D IOS data, the following dental characteristics were observed; restorations, missing tooth, occlusal cavities-unrestored and anterior crowding of teeth.

7.2.1.1 Inclusion and Exclusion criteria:

Willing and interested participants aged 16 years and above who were able to provide consent were recruited for this study. Completely edentulous participants were not considered. Participant Information Sheets (Appendix - D) and consent forms (Appendix - E) were created and approved by the co-sponsors and ethics service for this research.

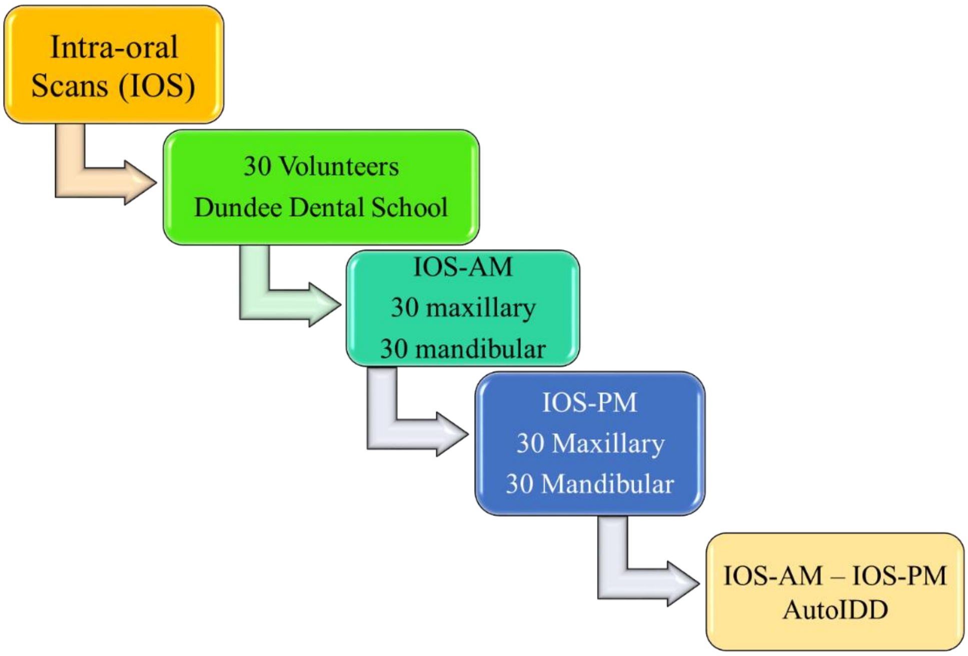


Figure 7.1 Outline of methodology using Maxillary and Mandibular AM-PM IOS.

Figure 7.2 3Shape TRIOS Intra-oral Scanner.

The study hypothesis is that an accurate dental identification may be facilitated through the use of AutoIDD software, regardless of a time interval between collection of records (the time interval representing the difference between AM records and PM records). The identification process is based on dental characteristics, shape and alignment of the 3D dental arches and any dental treatment interventions, and this study will test the ability of the software to match cases despite minor changes in the dentition over the period of a year.

7.2.2 Data processing using Full Arch IOS:

This part of the study was conducted by simulating a dental identification scenario. Thirty AM and 30 PM maxillary IOS were imported into the "reference" and "unknown" sections of the AutoIDD interface respectively. These were aligned for automated comparison (superimposed) and identification of correct matching pairs. This was followed by 30 AM and 30 PM mandibular IOS. Initially, all the maxillary and mandibular IOS were analysed separately to determine the accuracy of AutoIDD software within a specific type of dataset.

To determine the robustness of the software with different scanning methods (laser scanned models and Intra-oral Scanning) another 10% of data from each PM dataset (three from each of 30 3D models/IOS) were selected at random using an online random number generator tool. This sample comprised a total of 12 maxillary and mandibular dental models and IOS (six dental models and six IOS). For the purposes of the experiment, this sample was considered as "**test**" data. Twelve corresponding/matching 3D models and IOS were retrieved from the respective "reference" data. Additionally, 12

3D models and IOS were also selected at random and included with the 12 corresponding reference data totalling to 24. The 12 “test” data were aligned with 24 “reference” 3D models and IOS.

Once the data was processed, the results were displayed in a tabular form (vertical – reference data; horizontal – unknown / test data) for all the automated alignments. The statistical analysis of the study datasets were assessed using IBM® SPSS Package Version 22 (New York, USA).

7.2.3 Data processing using Pre-orthodontic and Post-orthodontic Dental Models:

Though the purpose of the AutoIDD software was to align and identify matching dental patterns in a given dataset, an experiment was designed to evaluate the performance of the software using pre-orthodontic (considered as AM) dental models and post-orthodontic (considered as PM) models. The pre-orthodontic models were selected at random. On analysis of the pre-orthodontic data, it appeared that the dental health component grades ranged from grade 2 to grade 5.

Eight sets of maxillary and mandibular pre-orthodontic dental models were aligned with their corresponding post-orthodontic models for automated identification. The pre-orthodontic and post-orthodontic dental models were considered as AM-PRE and PM-POST respectively. The data was processed and results were obtained.

7.3 Results

7.3.1 Results of Full Arch IOS

The results of the processed IOS also indicated that the software accurately identified the matching AM-PM IOS from the non-matches in all cases. The match percentage of the maxillary and mandibular IOS ranged from 65-100% and 81-100%, with a mean percentage of 96.7 and 96.4 respectively. A substantial difference in the match percentages and mean distances between a matching and non-matching pair was observed. The comparison of the mean distance, standard deviation and RMS of the "correct 3D" dental model (chapter 6) and IOS matches" (maxillary and mandibular) is shown in Table 7.1.

Analysis of the 3D IOS displayed a total of 900 automated comparisons and alignments (30 AM x 30 PM) for each data set. This resulted in 30 correct matches based on "best fit alignment" and 870 non-matches. This process validates the function of AutoIDD software. The match percentages of the corresponding AM and PM maxillary and mandibular IOS were indicated in green, as shown in Figs. 7.3 & 7.4.

Dental Arches	3D scans	AM Data (n)	PM Data (n)	Minimum Match percentage	Maximum Match percentage	Maximum Non-match percentage	Mean Distance (mm) of Correct matches	Mean Distance (mm) of Non-matches	Standard Deviation (mm) of Correct matches	RMS (mm) of Correct matches	RMS (mm) of Non-matches
Maxillary	Dental Models	30	30	-	100	7.7	0.075	0.76	0.006	0.03	1.00
	IOS	30	30	65	100	6.0	0.094	0.87	0.031	0.10	1.11
Mandibular	Dental Models	30	30	-	100	8.6	0.076	0.80	0.013	0.06	1.04
	IOS	30	30	81	100	6.3	0.093	1.00	0.027	0.11	1.30

Table 7.1 shows the results obtained from the automated comparison of both the AM-PM 3D datasets; Dental Models and IOS.

	MAX-PM-01	MAX-PM-0	MAX-PM-03	MAX-PM-04	MAX-PM-0	MAX-PM-0	MAX-PM-0	MAX-PM-0	MAX-PM-0	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-1	MAX-PM-2	MAX-PM-2	MAX-PM-2	MAX-PM-2	MAX-PM-24	MAX-PM-2	MAX-PM-2	MAX-PM-2	MAX-PM-2	MAX-PM-2	MAX-PM-30
MAX-AM-01	100	2.6	2.8	2.2	4.8	2.2	3.9	3.1	2.6	5.0	3.4	2.8	2.7	3.3	3.5	2.5	2.3	2.3	2.0	4.9	4.9	2.6	3.1	2.4	2.5	2.1	3.0	1.9	3.2	1.9
MAX-AM-02	2.8	100	2.6	2.7	2.5	4.1	2.9	3.0	3.6	3.0	2.3	2.9	2.0	2.6	3.4	1.8	2.6	3.7	3.0	2.5	2.5	5.2	3.9	2.4	4.9	2.9	3.1	1.9	2.9	2.3
MAX-AM-03	3.3	2.9	100	2.6	3.1	2.5	3.7	2.8	2.7	3.4	2.2	2.7	2.0	2.4	4.2	2.1	2.5	3.1	2.4	2.7	2.9	3.7	3.7	2.5	3.2	2.5	3.0	2.1	2.8	2.3
MAX-AM-04	2.4	2.9	2.7	100	2.3	2.6	2.5	2.5	2.3	2.8	2.2	2.2	1.7	2.5	2.6	1.8	2.7	3.2	2.4	2.2	2.4	3.1	2.7	2.5	2.7	2.6	3.5	2.3	2.9	2.7
MAX-AM-05	6.0	2.7	2.8	1.9	100	2.2	5.0	3.3	2.4	4.6	4.2	4.7	2.4	3.4	4.3	2.8	2.2	2.0	1.9	4.1	4.9	2.7	3.2	2.3	2.5	2.0	2.8	1.8	2.9	1.9
MAX-AM-06	2.1	4.6	2.3	2.3	2.1	100	2.7	2.2	3.7	2.3	2.2	2.5	1.6	2.0	3.3	1.7	3.4	3.7	5.2	1.8	2.0	3.4	2.6	3.8	3.1	4.5	2.7	4.9	3.7	2.8
MAX-AM-07	4.4	3.3	2.9	2.0	5.0	2.3	100	4.0	2.7	4.3	4.0	5.1	2.8	3.1	4.7	2.7	2.0	2.5	2.1	4.3	4.2	3.6	6.0	2.3	4.0	2.0	2.7	2.1	2.8	1.9
MAX-AM-08	3.0	3.2	2.4	2.0	2.8	2.0	3.2	96.1	2.3	3.7	2.6	2.8	2.7	3.5	2.8	2.1	1.9	2.3	1.9	3.1	3.9	3.3	3.3	2.1	2.9	1.8	2.6	1.9	2.2	1.8
MAX-AM-09	2.7	3.1	1.9	2.1	2.6	3.5	3.0	2.2	100	2.6	2.7	3.3	1.7	2.1	4.3	1.8	2.9	2.3	2.3	2.0	2.3	1.8	1.8	3.2	1.7	3.1	1.8	1.6	3.2	2.3
MAX-AM-10	4.7	3.2	2.7	2.1	3.9	2.2	3.6	4.3	2.9	100	3.3	3.4	2.6	2.8	3.2	2.3	2.0	2.3	1.9	3.6	4.7	2.6	2.9	2.4	2.5	2.1	2.4	1.8	2.3	1.9
MAX-AM-11	3.6	2.5	2.6	2.4	3.9	2.3	4.3	3.1	2.4	3.9	100	4.2	2.4	2.7	3.4	2.4	2.0	2.2	1.9	3.4	3.8	3.2	3.5	2.6	2.9	2.1	3.1	1.9	2.4	1.9
MAX-AM-12	3.5	3.9	2.7	2.3	3.9	2.8	4.8	3.5	3.4	4.1	4.2	79.4	2.1	2.9	5.2	2.4	2.3	2.8	2.2	3.0	3.6	4.0	4.7	3.1	4.4	2.4	3.0	1.9	2.9	2.3
MAX-AM-13	2.7	2.1	1.8	1.6	1.9	1.6	2.3	2.8	2.2	2.7	2.4	2.2	99.5	2.1	2.0	2.0	1.4	1.6	1.6	2.6	2.8	1.9	2.1	1.8	1.9	1.5	1.9	1.3	1.7	1.3
MAX-AM-14	3.0	2.7	2.2	2.0	2.9	2.2	2.9	3.5	2.3	2.8	2.7	2.7	2.6	100	3.0	2.9	2.2	2.2	1.9	2.8	3.2	2.5	2.8	2.0	2.6	2.2	2.9	1.8	2.5	1.9
MAX-AM-15	3.3	3.2	2.9	2.4	3.9	3.2	4.7	3.0	3.8	3.3	3.8	4.8	1.9	3.0	100	2.2	2.9	2.8	2.5	2.5	2.9	3.3	4.0	3.0	3.7	2.7	2.4	2.2	3.6	2.6
MAX-AM-16	1.3	1.5	1.9	1.6	1.7	1.1	1.5	1.5	1.2	1.3	1.1	1.1	1.2	1.5	1.3	98.6	1.1	1.5	1.2	1.4	1.6	1.8	1.9	1.1	1.8	1.0	2.1	1.6	1.2	1.1
MAX-AM-17	2.6	3.0	2.0	2.3	2.8	3.4	2.4	2.1	3.1	2.4	2.3	2.5	1.5	2.3	3.0	1.9	100	3.2	2.3	1.8	2.1	2.5	2.6	3.2	2.2	3.4	2.7	2.9	3.7	2.3
MAX-AM-18	2.5	3.8	2.6	2.7	2.1	3.9	2.6	2.3	3.5	2.5	2.2	2.4	1.5	2.1	2.9	1.7	3.1	93.8	2.6	1.9	2.1	3.0	2.6	3.2	2.6	3.9	2.7	2.0	3.2	2.4
MAX-AM-19	2.0	3.9	2.5	2.7	2.0	5.8	2.5	2.1	3.2	2.2	2.2	2.3	1.6	2.0	3.0	1.6	3.0	3.3	100	1.8	1.8	3.0	2.4	2.9	2.7	3.9	2.4	4.1	3.3	4.8
MAX-AM-20	5.6	2.8	2.2	1.8	4.2	2.1	3.2	3.6	2.6	4.8	3.6	3.6	3.3	3.2	3.1	2.3	2.0	2.1	2.1	100	4.0	2.7	3.7	2.3	2.7	1.9	3.2	1.7	2.5	1.7
MAX-AM-21	4.9	2.8	2.1	2.0	4.2	1.9	3.1	4.3	2.2	4.7	3.7	3.4	3.0	3.7	3.1	2.9	1.8	2.2	1.8	4.0	100	3.2	3.8	2.2	3.2	1.8	3.4	1.8	2.3	1.9
MAX-AM-22	2.9	4.7	3.0	2.9	3.0	3.1	3.6	3.5	3.1	3.1	2.8	3.6	2.0	2.9	4.4	2.1	2.5	3.3	2.6	2.7	2.9	98.9	4.8	2.6	4.7	2.6	4.1	2.2	2.9	2.6
MAX-AM-23	3.6	3.5	2.9	2.5	3.8	2.9	5.3	3.4	3.6	3.5	3.2	4.3	2.4	3.0	5.5	2.2	2.4	2.8	2.4	3.4	3.4	4.8	89.7	3.1	4.6	2.5	2.7	2.0	3.2	2.3
MAX-AM-24	2.5	3.9	2.5	2.6	2.5	4.1	2.7	2.4	3.4	2.5	2.5	2.8	1.8	2.2	3.0	1.8	3.1	3.5	2.3	2.1	2.2	3.1	3.1	100	3.1	5.1	3.1	2.1	3.2	2.2
MAX-AM-25	3.2	5.1	2.5	2.4	2.9	2.8	3.7	3.1	3.2	2.8	2.5	3.7	2.0	2.8	4.1	2.0	2.2	3.0	2.3	2.9	2.9	5.0	4.4	2.9	91.1	2.3	3.4	2.2	2.7	2.4
MAX-AM-26	2.3	3.8	2.3	2.4	2.3	4.7	2.6	2.1	3.4	2.3	2.1	2.3	1.7	2.3	2.9	1.9	3.2	4.2	2.3	1.9	2.1	3.2	2.9	4.4	2.6	91.6	3.0	3.3	3.3	3.9
MAX-AM-27	3.7	3.5	2.4	2.8	3.3	2.6	3.4	3.2	2.7	3.0	3.0	3.0	2.3	3.3	3.6	2.4	2.5	2.7	2.4	3.1	3.2	4.3	4.3	2.6	3.3	2.6	100	2.3	3.4	2.7
MAX-AM-28	2.5	3.8	2.4	2.7	2.3	6.1	2.7	2.2	3.2	2.2	2.5	2.8	1.6	2.4	3.1	2.1	4.0	3.5	3.8	2.0	2.3	2.9	2.6	3.4	2.7	4.3	3.1	64.6	3.3	3.0
MAX-AM-29	2.7	2.9	2.3	2.4	2.6	3.5	2.6	2.3	3.1	2.5	2.6	2.7	1.5	2.2	2.9	1.6	2.8	2.5	2.9	2.0	2.2	2.2	2.3	3.0	1.9	3.1	2.2	2.3	100	2.6
MAX-AM-30	2.2	4.7	2.5	2.8	2.4	3.3	2.7	2.3	3.4	2.5	2.1	2.5	1.5	2.2	3.4	1.9	4.0	5.0	4.9	1.8	2.1	3.5	2.6	3.5	3.3	4.9	2.9	5.1	3.5	100

Figure 7.3 Match percentages of AM – PM maxillary IOS. The correct matching pairs are indicated in green and the maximum non-match percentage is shown in blue.

	MAND-PM-0	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM	MAND-PM-30
MAND-AM-01	97.9	2.5	2.0	2.9	1.7	1.4	2.5	2.8	1.8	3.7	2.8	1.8	2.1	1.9	3.7	2.4	1.9	1.8	1.8	3.2	3.2	2.6	1.6	1.5	2.9	2.6	3.2	1.9	2.9	2.5
MAND-AM-02	2.6	88.5	2.3	2.4	1.4	3.7	2.7	2.5	4.3	2.2	2.2	3.6	1.7	2.4	3.4	3.1	3.2	3.1	2.8	2.1	2.5	3.7	5.3	2.5	3.4	5.0	3.3	1.9	3.9	6.0
MAND-AM-03	2.4	2.2	99.9	2.8	2.0	2.0	3.4	1.9	2.1	3.2	2.3	2.8	1.3	1.7	3.0	2.4	1.5	1.7	2.5	2.6	2.2	3.4	2.6	2.2	3.6	1.9	3.0	2.1	2.1	2.3
MAND-AM-04	2.1	2.2	2.2	91.0	2.0	1.6	2.2	2.1	2.0	3.5	3.3	2.7	2.3	2.2	3.5	2.7	1.7	2.0	2.6	2.7	2.9	2.5	1.8	1.4	4.2	2.2	2.4	1.4	2.4	2.2
MAND-AM-05	1.5	2.4	2.3	1.4	87.3	2.3	3.0	1.8	3.1	1.7	2.8	3.1	1.2	1.8	1.8	3.2	2.5	1.9	2.4	1.2	3.3	2.2	2.6	2.3	2.7	2.2	1.7	1.1	2.2	2.4
MAND-AM-06	2.3	5.0	2.0	2.2	1.7	100	2.4	2.3	2.8	2.1	1.9	2.3	1.8	1.9	2.7	2.5	2.4	2.8	2.1	1.9	2.2	3.3	3.2	1.7	2.8	4.2	3.0	1.8	3.0	5.6
MAND-AM-07	3.2	2.7	3.3	2.6	0.3	2.4	100	2.0	3.8	4.7	3.3	3.6	1.3	1.8	5.0	2.4	2.3	1.9	3.2	4.4	2.9	4.1	3.3	3.3	4.9	2.0	4.0	1.8	2.7	2.7
MAND-AM-08	1.9	2.4	1.5	2.6	1.2	1.8	1.6	100	2.3	1.8	2.3	2.1	3.6	2.5	2.3	3.6	2.4	2.4	1.7	1.9	2.7	1.8	1.6	1.5	2.0	3.0	2.1	1.8	3.2	2.2
MAND-AM-09	1.2	2.4	2.2	1.0	1.1	3.0	2.3	1.3	100	1.3	1.2	2.2	1.5	2.0	1.6	1.5	3.1	2.2	2.5	1.4	1.3	2.1	2.5	2.6	1.9	2.6	1.7	1.3	2.3	2.4
MAND-AM-10	3.9	2.1	3.0	3.0	1.1	1.5	3.9	1.8	2.7	100	3.2	2.1	1.3	1.5	3.5	2.9	1.7	1.6	2.9	4.0	3.9	2.8	2.1	1.8	3.6	1.9	3.0	1.5	2.2	2.2
MAND-AM-11	1.7	2.2	2.0	2.1	1.4	1.6	2.4	2.1	2.3	2.0	100	2.1	1.8	1.7	1.9	2.8	1.9	1.7	2.2	2.2	3.8	2.2	2.0	1.8	2.5	2.0	1.7	1.2	2.0	2.0
MAND-AM-12	2.5	4.2	2.7	3.1	0.3	3.1	3.5	2.6	3.5	2.5	2.4	100	1.7	2.6	3.7	3.8	2.4	2.6	2.7	2.7	2.6	3.3	3.6	2.9	3.6	3.5	3.2	1.4	4.0	3.6
MAND-AM-13	1.5	1.4	1.2	2.3	1.1	1.4	1.2	2.7	1.7	1.9	1.2	1.2	83.3	1.9	2.2	1.9	1.4	1.6	1.2	1.3	1.0	1.3	1.4	1.3	1.2	2.0	1.6	2.9	1.8	1.4
MAND-AM-14	2.0	2.8	1.8	2.4	0.6	2.3	2.1	2.7	2.4	1.6	1.9	2.4	2.2	98.4	2.1	2.4	2.3	2.3	2.1	1.7	2.0	2.3	2.4	1.7	2.4	2.7	2.2	2.6	3.8	2.5
MAND-AM-15	3.2	3.1	2.7	2.6	1.4	2.1	4.9	2.1	4.4	3.4	3.1	3.2	1.4	2.2	93.2	2.4	2.2	2.1	3.0	3.1	3.2	3.6	3.2	2.2	4.3	2.6	2.7	1.4	3.2	3.1
MAND-AM-16	2.4	2.9	2.0	2.2	0.8	2.3	2.0	3.5	0.9	2.8	2.6	2.1	1.0	2.4	2.7	97.6	2.6	3.0	2.6	1.5	3.6	2.6	2.3	2.0	2.8	2.9	2.6	2.2	3.0	2.8
MAND-AM-17	2.5	3.3	2.0	2.4	0.3	3.3	2.3	3.0	3.5	2.0	2.3	2.9	1.9	2.5	2.9	2.8	100	3.5	2.2	2.3	2.4	2.3	3.1	2.4	2.4	3.6	2.5	2.1	3.6	3.2
MAND-AM-18	1.6	2.3	1.5	1.6	1.9	1.9	1.6	2.7	2.5	1.4	1.7	2.2	2.4	2.3	1.8	3.1	2.4	94.7	1.8	1.4	1.9	1.8	1.8	1.6	1.8	3.0	1.7	1.3	2.8	2.4
MAND-AM-19	2.7	2.9	3.0	2.7	0.2	2.7	3.3	1.8	3.2	3.1	2.6	2.8	1.5	1.7	3.1	2.8	2.0	1.9	100	2.8	2.6	3.3	2.9	2.7	3.7	1.9	3.1	1.1	2.4	2.6
MAND-AM-20	3.4	2.5	2.7	2.4	2.9	2.1	4.4	2.0	3.1	4.9	3.6	3.1	1.3	1.9	3.6	2.6	2.2	1.8	2.4	100	3.5	2.9	2.7	2.4	3.4	2.2	3.2	1.8	2.6	2.7
MAND-AM-21	2.9	2.4	1.9	3.1	0.9	1.7	2.3	2.6	2.7	3.4	3.9	2.1	2.7	1.8	3.0	3.8	2.0	1.9	2.4	2.9	100	2.3	1.9	1.5	2.5	2.3	2.5	1.7	2.4	2.3
MAND-AM-22	2.7	4.3	3.0	3.2	1.6	1.8	3.3	2.4	2.3	2.7	2.5	2.5	2.0	2.3	3.7	1.6	2.0	2.0	2.8	2.5	2.6	95.6	3.6	1.8	5.2	3.0	3.6	2.7	3.3	3.9
MAND-AM-23	2.6	5.5	2.5	2.6	1.5	2.3	3.2	2.6	3.0	2.5	2.8	3.3	1.7	2.3	4.5	2.8	2.4	2.6	2.4	2.3	2.9	3.9	96.9	2.3	3.9	3.8	3.2	2.1	3.1	5.6
MAND-AM-24	3.1	2.6	2.7	2.9	0.2	1.8	4.0	2.2	2.3	3.2	2.5	2.6	1.6	1.9	3.9	2.4	2.0	2.0	2.4	2.9	2.5	3.9	3.1	86.1	3.9	2.6	3.8	2.2	2.5	3.4
MAND-AM-25	2.8	3.4	3.3	3.0	2.5	2.8	4.0	2.0	2.9	3.3	2.8	3.4	1.4	1.9	3.9	2.8	2.1	2.0	3.2	2.9	2.6	5.3	3.7	2.9	99.8	2.9	3.5	2.2	2.8	3.4
MAND-AM-26	2.6	5.5	2.2	2.9	0.4	2.7	2.3	3.5	2.5	2.2	2.2	3.1	2.2	2.5	3.0	3.0	3.5	3.3	2.2	2.0	2.5	3.1	3.8	2.1	2.9	81.9	3.0	2.5	3.8	4.9
MAND-AM-27	3.9	3.2	3.0	2.9	1.3	2.7	3.7	2.0	2.7	3.4	2.5	3.1	1.4	2.1	3.4	2.4	2.3	2.2	2.9	3.4	2.6	3.6	3.6	2.6	3.8	2.7	100	2.0	3.1	3.6
MAND-AM-28	2.1	2.1	1.0	3.2	1.2	1.2	1.7	2.5	1.8	1.9	1.8	1.7	3.0	2.2	2.3	2.5	2.0	1.8	1.6	1.9	2.1	2.0	1.7	1.2	1.8	2.2	2.2	100	2.4	2.1
MAND-AM-29	2.5	3.1	1.9	2.6	1.3	2.3	2.5	3.1	3.6	2.0	2.3	3.1	2.0	3.6	2.9	3.4	2.7	2.4	2.2	2.1	2.6	2.5	2.1	1.9	2.6	3.3	2.4	1.9	100	3.3
MAND-AM-30	2.5	6.3	2.6	2.3	2.5	5.7	2.8	2.2	3.8	2.3	2.4	3.6	1.5	2.3	3.4	3.0	3.9	3.1	2.6	2.1	2.5	3.7	5.9	3.0	3.5	4.7	3.3	1.9	3.6	100

Figure 7.4 Match percentages of AM – PM mandibular IOS. The correct matching pairs are indicated in green and the maximum non-match percentage is shown in blue.

The analysis of the total comparisons in each group (maxillary and mandibular 3D IOS) shows the match percentage and histogram of data distribution, see Fig. 7.5 & 7.6. Fifteen percent (approximately ten) of the total 3D IOS data (60) was also processed to demonstrate the robustness in differentiating maxillary and mandibular arches (Fig. 7.7).

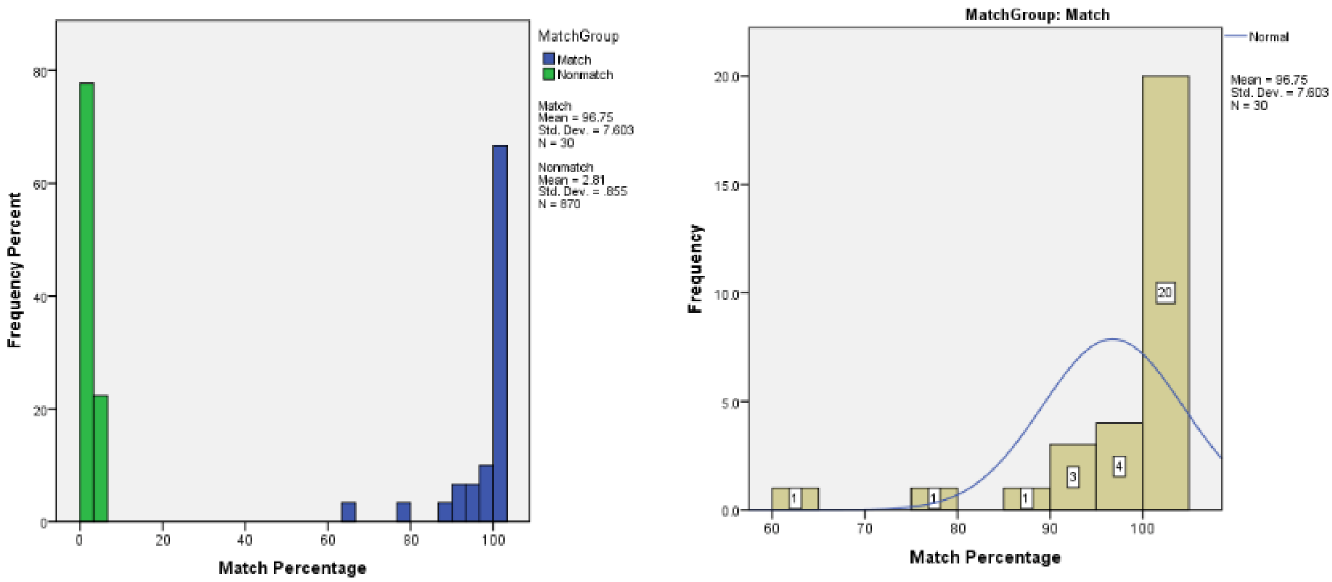


Figure 7.5 Histogram of the distribution of percentage of matches and non-matches of maxillary IOS.

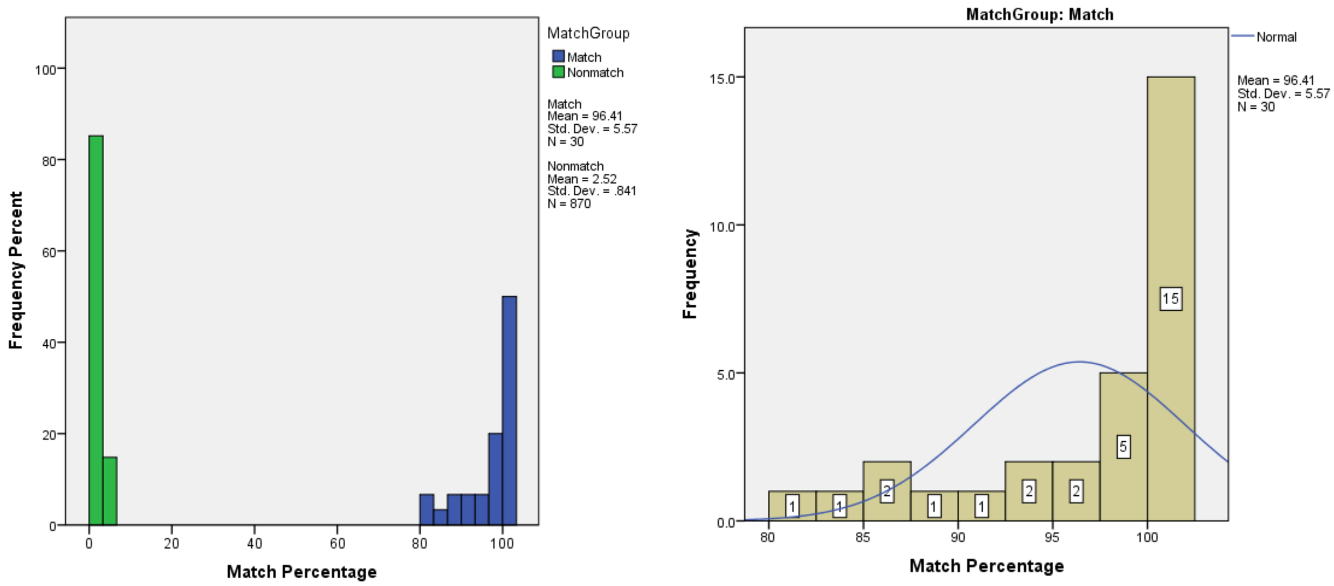


Figure 7.6 Histogram of the distribution of percentage of matches and non-matches of mandibular IOS.

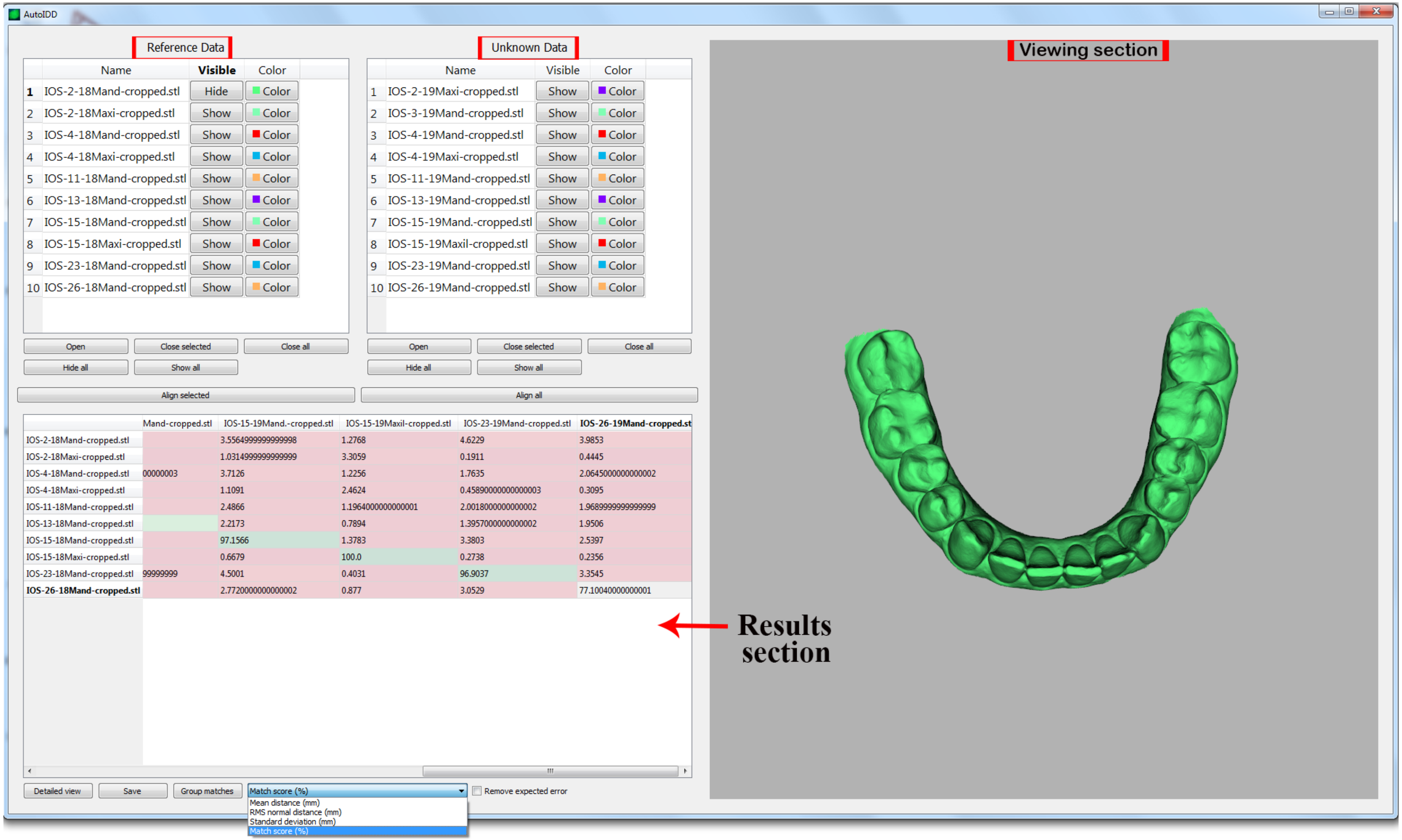


Figure 7.7 shows the results of a processed IOS data along with the result interpretation drop-down list.

Alterations or changes in the dentition (occlusal or any tooth surface) were illustrated in red. For example, a restoration present in the “unknown” scan and not in the “reference” scan is depicted in areas of red, see Fig. 7.8 (b,d), while an incorrect alignment of a non-match is shown in Fig. 7.9 a. A colour scale on the superimposition map displays the quantitative differences between the reference points of arches.

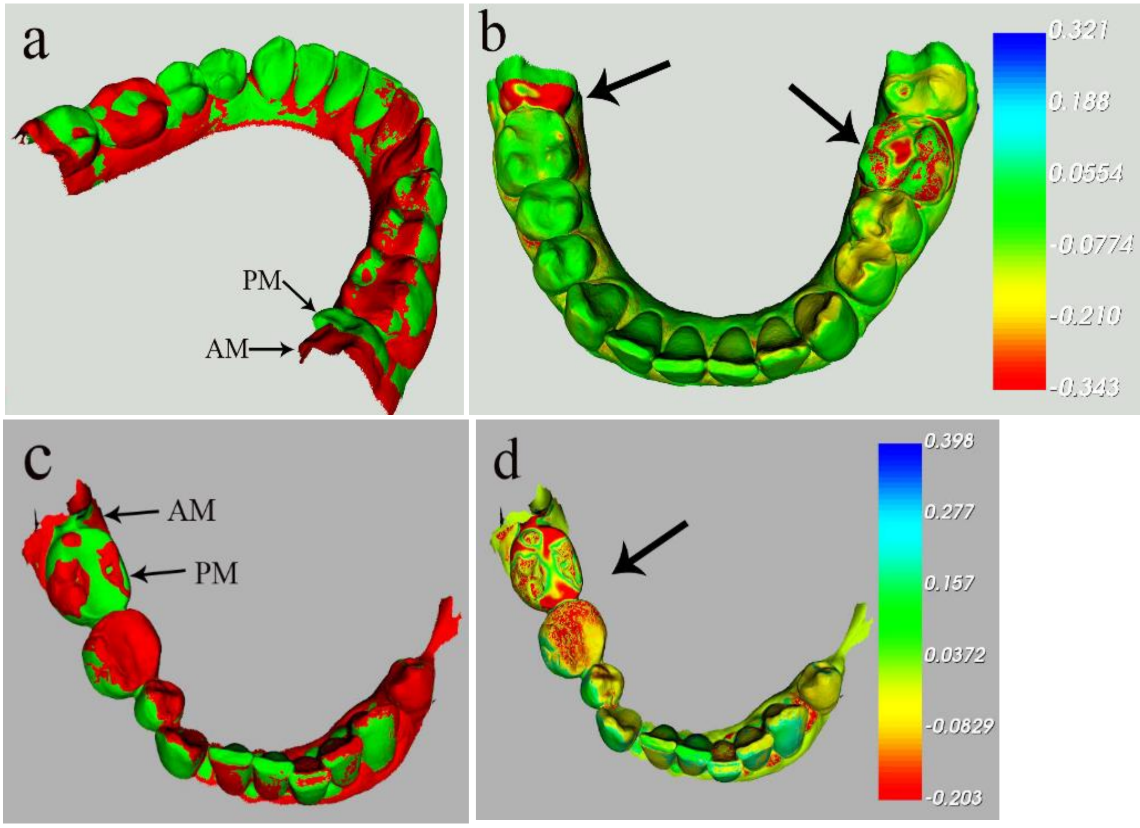


Figure 7.8 shows the colour maps of two AM (Red) – PM (Green) IOS pairs. Examples of correct alignments (a, c) and superimpositions (b, d) of matching pairs. The match percentage of 3D pair “b” – 88.5% while for pair “d” - 83.2% due to alterations in the dental scans such as loss of tooth structure or restorations (indicated by arrows).

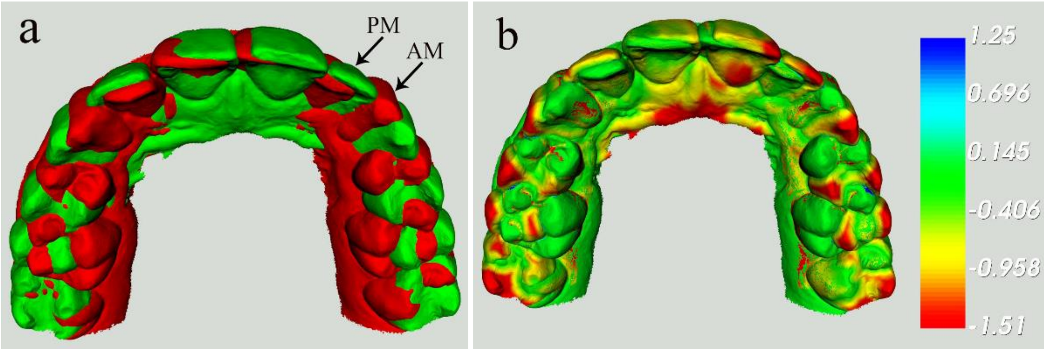


Figure 7.9 Example of an incorrect alignment (a) and superimposition (b) of a non-matching AM (Red) – PM (Green) IOS pair.

The results of the "**test**" data (different type of 3D scans) revealed that the AutoIDD software clearly differentiated maxillary and mandibular arches and accurately identified correct matching pairs among other non-matches, see Fig. 7.10. The results (match percentage and mean distances) were consistent with the previous outcomes.

Overall, it was possible to identify all the correct matching pairs through the AutoIDD software. The results from the automated comparison and alignment of different types of scans were consistent. There were no scans or matching pairs with similar or close match percentage or mean distance within the processed dataset. The availability of AM 3D data has potential to allow for an accurate digital comparison with the PM 3D data which can be applied in single identification cases.

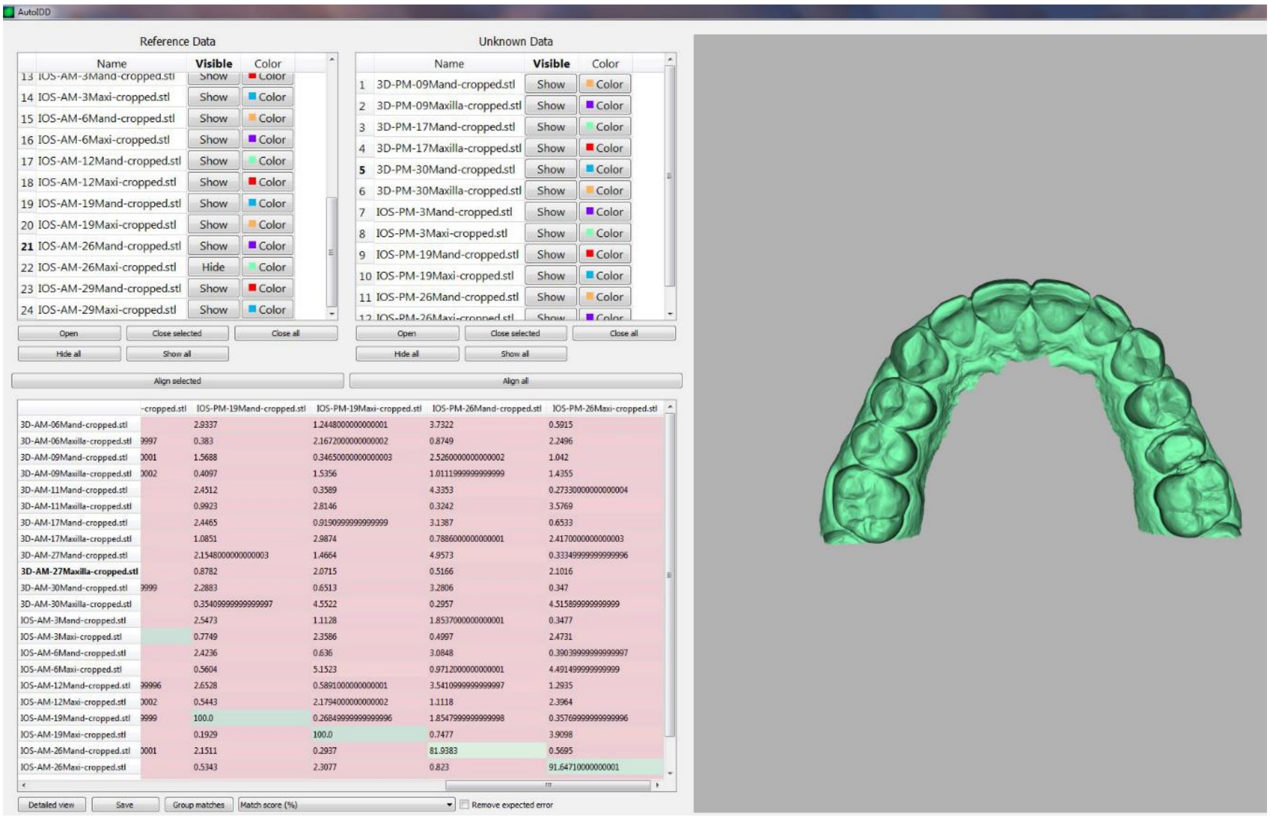
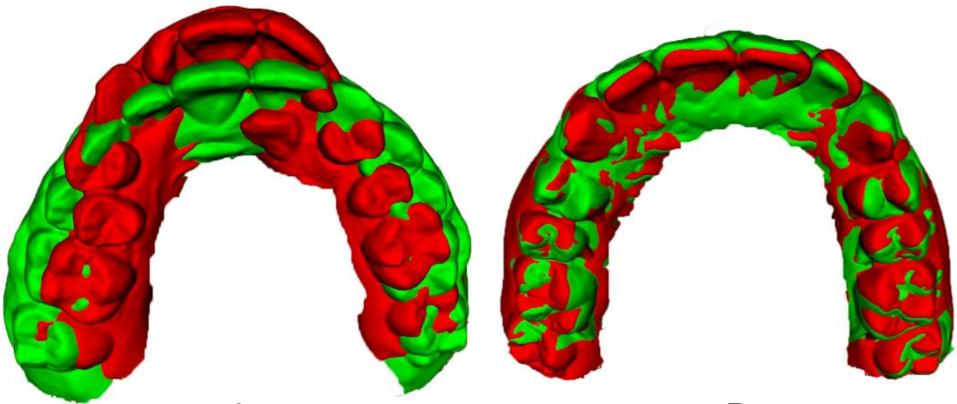


Figure 7.10 AutoIDD software clearly differentiated maxillary and mandibular arches as demonstrated in the results section.

7.3.2 Results of Pre-orthodontic and Post-orthodontic Dental Models.

Of the 16 pre- and post-orthodontic AM-PM 3D pairs, 11 pairs were correctly identified while five pairs were falsely identified (Fig. 7.12). The match percentages of correct AM-PM 3D pairs was reduced and ranged from 1.78 % to 53.2 %. The least match percentage (1.78 %) was for the model with severe malocclusion or with a grade 5 dental health component present (Fig. 7.11 A), while the highest (53.2 %) was for the model with mild malocclusion or with a grade 2 dental health component (Fig. 7.11 B). The alignment images of the pre – and post-orthodontic models are shown in Fig. 7.11 A & B respectively.



A B

Figure 7.11 The alignment of the 3D pair A produced the least match percentage (1.78 %) with a high probability of false positives due to the severity of malocclusion. The 3D pair B produced the highest match percentage (53.2 %) due to minor differences in the pre-orthodontic model.

	PM-16Mand	PM-16Maxill	PM-17Mand	PM-17Maxil	PM-18Mand-	PM-18Maxill	PM-19Mand	PM-19Maxil	PM-20Mand-	PM-20Maxi	PM-23Mand-	PM-23Maxil	PM-25Mand	PM-25Maxilla	PM-26Mand-	PM-26Maxil
AM-PRE-1-Mand-	3.83%	0.42%	2.73%	0.85%	2.66%	1.13%	2.53%	0.39%	1.66%	0.29%	5.03%	0.42%	2.01%	0.34%	2.51%	0.52%
AM-PRE-1-Maxill	0.72%	3.29%	1.02%	3.44%	0.39%	3.42%	0.45%	2.71%	0.42%	3.26%	1.49%	4.04%	0.76%	2.40%	0.87%	4.14%
AM-PRE-2-Mand-	2.68%	0.70%	3.70%	0.82%	2.93%	0.26%	2.69%	1.08%	2.22%	0.15%	3.06%	0.30%	2.39%	0.37%	2.98%	0.73%
AM-PRE-2-Maxill	0.52%	3.03%	0.95%	4.06%	0.33%	2.62%	0.46%	3.50%	0.33%	3.04%	0.78%	3.32%	1.01%	2.39%	0.84%	2.72%
AM-PRE-3-Mand-	1.48%	0.27%	4.69%	0.26%	7.42%	0.82%	4.16%	0.80%	2.84%	0.91%	2.86%	0.13%	3.01%	0.35%	3.56%	0.33%
AM-PRE-3-Maxill	0.32%	2.22%	0.39%	2.47%	0.32%	6.82%	0.29%	2.30%	0.36%	2.97%	0.34%	2.56%	1.17%	2.04%	0.36%	3.35%
AM-PRE-4-Mand-	2.15%	0.72%	3.00%	0.30%	3.46%	0.72%	3.47%	0.30%	2.20%	0.97%	3.70%	0.92%	2.40%	0.37%	4.10%	0.99%
AM-PRE-4-Maxill	0.46%	1.41%	0.43%	1.53%	0.44%	1.31%	0.92%	1.78%	0.61%	1.32%	0.79%	1.73%	0.94%	1.13%	0.49%	1.33%
AM-PRE-5-Mand-	1.28%	0.27%	3.23%	0.32%	3.70%	0.54%	2.82%	0.89%	3.95%	0.23%	1.93%	0.17%	3.10%	0.28%	2.77%	0.29%
AM-PRE-5-Maxill	0.37%	2.61%	0.33%	2.46%	0.71%	3.07%	0.44%	2.28%	0.22%	3.36%	0.45%	3.23%	1.02%	2.61%	0.32%	3.42%
AM-PRE-9-Mand-	3.09%	1.10%	3.18%	0.92%	3.40%	1.15%	3.21%	0.99%	2.34%	0.28%	14.21%	1.03%	2.51%	0.87%	4.98%	0.64%
AM-PRE-9-Maxill	0.64%	3.54%	1.10%	4.28%	1.05%	3.75%	0.70%	3.65%	1.08%	3.92%	0.81%	53.21%	0.37%	2.92%	0.84%	5.04%
AM-PRE-11-Mand	1.99%	0.30%	2.46%	0.51%	2.94%	0.35%	2.98%	0.79%	2.13%	0.37%	2.97%	0.96%	2.77%	0.38%	3.06%	0.25%
AM-PRE-11-Maxil	0.56%	2.02%	0.45%	2.31%	0.90%	2.15%	0.58%	2.06%	0.83%	2.34%	0.91%	2.92%	0.92%	4.21%	0.42%	2.24%
AM-PRE-12-Mand	2.06%	0.72%	3.36%	0.47%	3.62%	0.73%	3.60%	0.74%	2.82%	0.30%	3.34%	0.32%	2.88%	0.41%	5.52%	0.56%
AM-PRE-12-Maxil	0.78%	3.09%	1.13%	3.80%	0.21%	4.50%	1.06%	3.63%	0.58%	4.05%	0.41%	4.05%	1.12%	2.35%	0.80%	8.67%

Figure 7.12 Match percentages of AM - PM models. The correct matching pairs are indicated in green while red indicates falsely positives due to higher match percentage.

7.4 Discussion

This study demonstrates the feasibility of using 3D dental models and IOS in the new automated software (AutoIDD) for efficient and accurate dental identification. There is a shift towards digital storage of dental records, facilitated by affordable 3D scanners which can digitise the patient's dental casts (Martin et al., 2015). Through the increasing use of 3D scanners and chairside intra-oral scanners (Chalmers et al., 2016), 3D dental models may be considered a useful source of AM information. All the scientific primary methods of human identification (fingerprint, DNA analysis, and dental) involve the comparison of the AM data to PM evidence to establish a positive identification (Caplova et al., 2018). Furthermore, the dental characteristics; their alignment and orientation within the arch, tooth shape and dental treatment interventions were considered for a dentition to be unique (Franco et al., 2015).

Using registration techniques, the likelihood of finding matching dentitions in a given population were conducted in 2D (Kieser et al., 2007, Bush et al., 2011b, Sheets et al., 2011). In the process of investigating the uniqueness of the human dentition, few attempted matching studies on 3D scanned dentitions (Bush et al., 2011a, Sheets et al., 2013), while orthodontically treated samples were evaluated in 3D using semi-automatic methods (Franco et al., 2017, Dyke et al., 2018) which were all landmark based. All of these studies examined only the upper and lower anterior teeth. A pilot study (Chong and Forgie, 2017) analysed the incisal edges (2 mm) of the six anterior teeth of post-orthodontic treated dentitions using 3D software packages for identifying matching set of dentitions. The study concluded that the human anterior dentition is unique and encouraged a 3D approach, however, it required manual segmentation and lacked complete automation.

The study data consisted of random individuals from the general population relevant only to the locality. In a forensic setting, though equal number of corresponding or matching 3D reference scans were considered during the automated process, there was only one correct AM match in the reference data for every PM case. The remaining 29 were non-matches. The AutoIDD was found to be consistent in accuracy; capable of identifying “correct matches” from “non-matches” by assigning a high match percentage for correct match and a very low for a non-match.

In the context of a forensic identification case, there may be more than one AM dental record to compare with one PM dental record if a number of individuals are missing, the authorities may suspect that the unidentified deceased could be any one of the indicated missing persons. Therefore, the automated process was subjected to test the performance with an increased number of AM non-matches/cases with a “**test**” data. The software demonstrated its robustness in efficiently performing with different types of 3D scans, see Fig. 7.10.

The important outcome of the AutoIDD software is that, for a correct match the match percentage is higher than other scores and it narrows down to the correct AM correspondence (indicated in green), see Figs. 7.3 & 7.4. Hence, low or high match percentage is not only the point, but needs to be discriminatory. For example when a 65% is assigned to a PM-1 and AM-1 3D pair and the next nearest match percentage for PM-1 and AM-2 is approximately 3%, and no other pair has a higher match percentage, it indicates that PM-1 and AM-1 is the best matching pair for that PM model. All these numbers are content dependent; variations in the dentitions, see Fig.7.8. Similarly, 100%

means that within the precision of the software and within the boundaries of its margin for error, it is able to determine that it is an exact match, i.e. best fit match.

The IOS data had some dental alterations (therapeutic and non-therapeutic) during the scan interval. Many of the changes a tooth can undergo are by their nature irreversible. These discrepancies are significant during the comparison process and must be evaluated by the forensic expert as to whether they are explainable or unexplainable (Carabott, 2013). An ‘explainable discrepancy’ is one where an unrestored tooth/teeth surface(s) in AM model is found to be restored in the PM model. While a tooth/teeth present in the PM model and missing in the AM model would usually be considered as an ‘unexplainable discrepancy’ (with the exception of unerupted teeth subsequently erupting). The sensitivity towards any changes in the dentition can be appreciated with the help of colour maps generated for every 3D pair. It was also noticed that the influence of soft tissues on the overall result/score was negligible when compared to the dental component.

The evidence presented in this part of the study strongly suggests that for a given comparison, the correct match will be the one with the highest match percentage and lowest mean value. It was observed that the accuracy of the alignment process and the match percentage increased when there was greater similarity between the dentitions being compared. Where changes in the dentition had occurred between scans, the match percentage was reduced. In addition, the whole arch presentation may enhance the overall reliability of the identification process.

The density in an area of the IOS may also increase during the scanning process where the operator sometimes have to rescan a certain area of the teeth surfaces which are not adequately scanned. This can be very detrimental. Imbalance in the model causes the centre of mass to be pulled towards those denser areas and the axes will be unreliable. The scanner used throughout this study (3Shape Trios intra-oral scanner) yields two STL files. A ‘raw’ one as the output file and a ‘normalised’ one. Normalisation of 3D models is a common pre-processing stage in many applications in computer graphics, such as, visualisation, 3D object recognition, 3D shape matching and retrieval. 3D models are generally given an arbitrary scale, position and orientation in 3D-space (Bustos et al., 2004, Tangelder and Veltkamp, 2004). In this normalised scan the more redundant points in the overly dense areas have been removed. This is primarily to reduce file size but has the added advantage of balancing the model density, resulting in a more accurate PCA.

The results obtained from the automated alignment and matching of the pre-orthodontic and post-orthodontic models indicate that the AutoIDD software has not been successful in achieving a desirable outcome for all cases tested; i.e. correct identification of pre- (AM) and post-orthodontic (PM) 3D pairs in all the given cases. This is not surprising, given the significant alignment of teeth during the process of orthodontics. From the above experiments, it is understood that significant changes in the dentition may affect the alignment and superimposition process leading to increased error values. An area of further research is to explore the potential to develop software that predicts orthodontic tooth movement for patients that have undergone orthodontic treatment, or to explore software to focus on tooth morphology rather than tooth alignment. This, however, would require scrupulous interrogation of the uniqueness of the morphology of the dentition. Removing alignment from the “uniqueness” equation is a future challenge.

The process of 3D comparison may potentially be considered in the Disaster Victim Identification techniques in future with the increased accessibility and use of 3D datasets (Forrest, 2019). With this in mind, the author would reinforce the recommendation to consider diagnostic and working casts as part of the dental record, and preserve them for several years following the completion of the dental treatment depending on the resident country's dental association's regulations and guidelines. Where identification is problematic by other means, and where AM dental models or scans are available, forensic odontologists are encouraged to obtain PM dental impressions. This would facilitate a process of automation in forensic identification. Furthermore, in a DVI setting, or for a single identification where there is not yet a suggested identity (i.e. AM records are not yet available), forensic odontologists are encouraged to obtain PM dental impressions whenever possible.

This is the first fully automated system which is intended to assist forensic experts in the process of dental identification. The performance of the AutoIDD has so far been successful only with full arch dental models and IOS. Through this study it is established that this automated identification system is consistent with the construct it is supposed to be measuring, which is a "proof of concept" and very encouraging in the early stages of development. The advantage of 3D format is the dimensional stability; correct size proportions, which is a limitation for the radiographs. Moreover, AutoIDD has the potential to be used in the digital retrieval of patient dental records from digital dental databases and in dental practices. Further research and software development is required in the investigation of pre- and post-orthodontic samples, partial remains and single tooth PM 3D models.

A strong distinction between a match and non-match, robustness with different scan types and overall efficiency and accuracy in achieving the results makes this study novel.

7.5 Conclusion

In summary, AutoIDD software was able to successfully demonstrate the identification of correct matches with a match percentage that clearly differentiates the matches from non-matches. This software also enables recognition of the changes in the human dentition, such as restorations and missing teeth. The match percentage is a combination of the “best fit alignment” and the morphological changes identified by the software. A low match percentage may also infer that there have been significant changes to that individual’s dentition usually due to dental intervention. These changes are also visible on the superimposition heat maps produced by the software, which enables identification of the exact location(s) of any differences in the superimposed models.

Chapter 8 - Strengths and Limitations of the Research

Photographic dental identification studies:

The 2D-3D superimposition method was an original study, at this time there are no reported studies that have investigated the reliability of a superimposition technique using 2D photographs of a smile and 3D dental models in dental identification. Any AM photographs or selfies available through personal phones or social networks can be considered as an additional source of images for dental identification while the 3D dental scans as PM models. This technique may be applied in forensic cases with inadequate or no AM dental records by obtaining PM impressions and digitising the dental cast or scans of the teeth whenever possible. The benefits includes spatial orientation of the 3D model with the smile and eliminates the requirement of multiple PM photographs.

Limitations of the method:

With regards to visibility, the photographs of a smile with a very limited teeth exposure and visibility of either maxillary and or mandibular anterior teeth without the incisal edges will affect the comparison process. The lack of identifiable unique dental features such as tooth morphology and alignment may decrease the likelihood of reaching a conclusion with higher certainty. Poor quality and severely distorted images (angular distortion) may not permit a 2D-3D superimposition procedure. Furthermore, traumatic injuries to the face may damage the anterior dentition or disrupt the alignment, which is a situation where photographic superimposition may not be indicated. Moreover, larger sample size is recommended for better reliability, particularly where comparisons were required between similar smiles, as in the case of post-orthodontic treated individuals.

The study with selfies was conducted using a small sample of selfie images and 3D dental scans of living individuals by simulating a dental identification scenario to demonstrate the applicability of 2D-3D superimposition method by the PI. This was simply a proof of concept study conducted by the PI without reference to all the raters and therefore inter-rater reliability was not tested for this preliminary pilot study. This study was designed as a pilot with a small sample, hence, a larger sample size with more forensic odontologists for inter-rater agreement would benefit the research.

AutoIDD study:

This study presents a novel method for automated dental identification using 3D scans which was developed with the innovative utility of python software, match percentage algorithm and image superimposition. AutoIDD software also eliminates the need for manual surface registration and segmentation. The prospective nature of the data collection allowed the recognition of changes in the dentition of the participant during the automated identification process.

Limitations of the software:

The software was unable to recognise and identify the target dental patterns of partially edentulous PM scans from the full arch AM reference models. It was also not successful in the correct identification of pre- (AM) and post-orthodontic (PM) 3D pairs in all the given cases. Significant changes in the dental pattern may affect the alignment and superimposition process leading to increased error values.

Chapter 9 - Conclusion

With increased assess to hand-held devices like smartphones, there has been a significant rise in the prevalence of smiling images (photographs and selfies) shared instantly on social networking sites such as Facebook, Instagram, Twitter, and WhatsApp. These can be considered as a potential AM source of dental images. Furthermore, through the evolving technology, 3D imaging introduces many advantages to future dental identifications, such as the dimensional stability of 3D format; correct size proportions.

This research relates to the challenges faced by a forensic odontologist in the area of forensic dental identification requiring photographs / cases with no dental records or inadequate for identification purposes. Improving the accuracy of an identification based on an AM 2D photograph of a person smiling with the aid of 3D technology at PM will assist forensic odontologists with human identification.

The certainty and accuracy of the conclusions reached was improved when using the 2D-3D superimposition method. The 3D approach provided more information for reaching a conclusion than 2D approach. This technique is possible, practical and effective.

This research also presented a new and fully automated software – Automated Identification from Dental Data (AutoIDD). The application of software to dental scans demonstrated its robustness in efficiently performing with different types of 3D scans. It was able to validate the identification of correct matches with a match percentage that clearly differentiates the matches from non-matches. Therefore, the AutoIDD software was found to be consistent and accurate.

Chapter 10 - Further Research

After overviewing this research, further research should be aimed at the following areas:

1. Application of the 2D-3D photographic / selfie superimposition method in a larger sample of images with different image views is recommended for better reliability, particularly where comparisons were required between similar smiles, as in the case of post-orthodontic treated individuals.

2. Development of a visibility criteria index for dental identifications using photographs based on the quality of the image and visibility of the teeth, particularly the incisal edges - usually of the maxillary incisors.

3. The performance of AutoIDD software in the investigation on the datasets with partially edentulous arches, fractured or partial dental remains / jaws, single tooth 3D models and dentitions of identical twins. With regards to pre- and post-orthodontic treated patient's 3D models, the software development should focus on individual tooth/teeth shape and not limiting to their alignment.

4. Development of a 3D image with the application of photogrammetry technology to a number of selfie images.

5. Finally, to work towards improving the presentation and precision of dental forensic evidence in courts in the absence of adequate AM dental records.

Appendices

APPENDIX - A

East of Scotland Research Ethics Service (EoSRES)

NHS SCOTLAND
Research Ethics Service

TAyside medical Science Centre
Residency Block Level 3
George Pirie Way
Ninewells Hospital and Medical School
Dundee DD1 9SY

Professor Peter Mossey
Professor and Honorary Consultant in Orthodontics
University of Dundee
Level 9, School of Dentistry
University of Dundee, Park Place
Nethergate, Dundee
DD14HR

Date:	27 November 2017
Your Ref:	
Our Ref:	LR/17/ES/0144
Enquiries to:	Mrs Lorraine Reilly
Direct Line:	01382 383878
Email:	eosres.tayside@nhs.net

Dear Professor Mossey

Study Title:	**Validation of Photographic methods for odontological comparison to aid in human identification**
REC reference:	**17/ES/0144**
IRAS project ID:	**236508**

Thank you for your letter received on the 24 November 2017, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair.

We plan to publish your research summary wording for the above study on the HRA website, together with your contact details. Publication will be no earlier than three months from the date of this opinion letter. Should you wish to provide a substitute contact point, require further information, or wish to make a request to postpone publication, please contact hra.studyregistration@nhs.net outlining the reasons for your request.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Conditions of the favourable opinion

The REC favourable opinion is subject to the following conditions being met prior to the start of the study.

You should notify the REC once all conditions have been met (except for site approvals from host organisations) and provide copies of any revised documentation with updated version numbers. Revised documents should be submitted to the REC electronically from IRAS. The REC will acknowledge receipt and provide a final list of the approved documentation for the study, which you can make available to host organisations to facilitate their permission for the study. Failure to provide the final

disability confident EMPLOYER

versions to the REC may cause delay in obtaining permissions.

1. Please ensure consistent version numbers are used across all documentation, as the version number and date in the table on page 1 of the protocol is different to the version number and date on the footer.

2. Thank you for inserting a simplified title on the healthy volunteer Participant Information Sheet (PIS), for consistency throughout the study documentation please insert the full title with the amended title underneath in brackets 'A study of photographic methods to aid in human identification' on both PIS's and consent forms.

The e-submission tab on IRAS has been enabled for uploading the revised protocol, PIS's and consent forms.

Management permission must be obtained from each host organisation prior to the start of the study at the site concerned.

Management permission should be sought from all NHS organisations involved in the study in accordance with NHS research governance arrangements. Each NHS organisation must confirm through the signing of agreements and/or other documents that it has given permission for the research to proceed (except where explicitly specified otherwise). Guidance on applying for NHS permission for research is available in the Integrated Research Application System, www.hra.nhs.uk or at http://www.rdforum.nhs.uk.

Where a NHS organisation's role in the study is limited to identifying and referring potential participants to research sites ("participant identification centre"), guidance should be sought from the R&D office on the information it requires to give permission for this activity.

For non-NHS sites, site management permission should be obtained in accordance with the procedures of the relevant host organisation.

Sponsors are not required to notify the Committee of management permissions from host organisations

Registration of Clinical Trials

All clinical trials (defined as the first four categories on the IRAS filter page) must be registered on a publically accessible database within 6 weeks of recruitment of the first participant (for medical device studies, within the timeline determined by the current registration and publication trees).

There is no requirement to separately notify the REC but you should do so at the earliest opportunity e.g. when submitting an amendment. We will audit the registration details as part of the annual progress reporting process.

To ensure transparency in research, we strongly recommend that all research is registered but for non-clinical trials this is not currently mandatory.

If a sponsor wishes to request a deferral for study registration within the required timeframe, they should contact hra.studyregistration@nhs.net. The expectation is that all clinical trials will be registered, however, in exceptional circumstances non registration may be permissible with prior agreement from the HRA. Guidance on where to register is provided on the HRA website.

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Ethical review of research sites

NHS sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Non-NHS sites

The Committee has not yet completed any site-specific assessment (SSA) for the non-NHS research site(s) taking part in this study. The favourable opinion does not therefore apply to any non-NHS site at present. We will write to you again as soon as an SSA application(s) has been reviewed. In the meantime no study procedures should be initiated at non-NHS sites.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Copies of advertisement materials for research participants [Study Poster]	1.0	02 October 2017
GP/consultant information sheets or letters [Study Summary for Dentists]	1.0	02 October 2017
IRAS Application Form [IRAS_Form_05102017]		05 October 2017
IRAS Application Form XML file [IRAS_Form_05102017]		05 October 2017
IRAS Checklist XML [Checklist_24112017]		24 November 2017
Letter from sponsor [Sponsor letter and Insurance Certificate]	3.0	03 October 2017
Letters of invitation to participant [Letter of Invitation]	1.0	02 October 2017
Other [Reply Slip_patient]	1.0	02 October 2017
Other [Gowri V Reesu-Protocol (highlighted changes)]	1.1	22 November 2017
Other [PIS-Patient (highlighted changes)]	2.0	22 November 2017
Other [PIS_HV (highlighted changes)]	2.0	22 November 2017
Other [Cover Letter EoSREC]		
Participant consent form [ICF_Patient]	1.0	02 October 2017
Participant consent form [ICF_HV]	1.0	02 October 2017
Summary CV for Chief Investigator (CI) [Chief Investigator CV]		
Summary CV for student [Student CV]	1.0	

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

<u>Reporting requirements</u>

The attached document *"After ethical review – guidance for researchers"* gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Notification of serious breaches of the protocol
- Progress and safety reports
- Notifying the end of the study

The HRA website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

User Feedback

The Health Research Authority is continually striving to provide a high quality service to all applicants and sponsors. You are invited to give your view of the service you have received and the application procedure. If you wish to make your views known please use the feedback form available on the HRA website: http://www.hra.nhs.uk/about-the-hra/governance/quality-assurance/

HRA Training

We are pleased to welcome researchers and R&D staff at our training days – see details at http://www.hra.nhs.uk/hra-training/

17/ES/0144	**Please quote this number on all correspondence**

With the Committee's best wishes for the success of this project.

Yours sincerely

pp
Dr Robert Rea
Chair

Email: eosres.tayside@nhs.net

Enclosures: “After ethical review – guidance for researchers”

Copy to: NHS Tayside R&D office
TASC

APPENDIX - B

NHS Tayside

06 April 2018

Dr G.V. Reesu
Level 8, PhD Hub-1
School of Dentistry
University of Dundee
2 Park Place
Dundee
DD1 4HR

Dear Dr Reesu,

Letter of Access for Research

NRS Project ID: n/a

Tayside R&D Project ID: 2017DE08

Research Title: PHOTO ID study - Validation of photographic methods for odontological comparison to aid in human identification

REC Ref: 17/ES/0144

Chief Investigator: Professor Peter A Mossey

NHS Tayside confirms your right of access to conduct research through their organisation for the purpose and on the terms and conditions set out below. This right of access commences on **06.04.2018** and ends on **01/06/2019** unless terminated earlier in accordance with the clauses below.

You have a right of access to conduct such research as confirmed in writing in the letter of permission for research from **NHS Tayside**. Please note that you cannot start the research until the Principal Investigator for the research project has received a letter from us giving confirmation of agreement to conduct the research.

The information supplied about your role in research in **NHS Tayside** has been reviewed and you do not require an honorary research contract with the organisation. We are satisfied that such pre-engagement checks as we consider necessary have been carried out. Evidence of checks should be available on request to the organisation.

You are considered to be a legal visitor to **NHS Tayside** premises. You are not entitled to any form of payment or access to other benefits provided by the organisation to employees and this letter does not give rise to any other relationship between you and the organisation, in particular that of an employee.

While undertaking research through **NHS Tayside** you will remain accountable to your substantive employer **University of Dundee** but you are required to follow the reasonable instructions of your nominated manager **Mrs Liz Coote, Head of Non-Commercial Research** in this organisation or those instructions given on their behalf in relation to the terms of this right of access.

Where any third party claim is made, whether or not legal proceedings are issued, arising out of or in connection with your right of access, you are required to co-operate fully with any investigation by **NHS Tayside** in connection with any such claim and to give all such assistance as may reasonably be required regarding the conduct of any legal proceedings.

You must act in accordance with **NHS Tayside** policies and procedures, which are available to you upon request, and the Research Governance Framework.

You are required to co-operate with **NHS Tayside** in discharging its/their duties under the Health and Safety at Work etc Act 1974 and other health and safety legislation and to take reasonable care for the health and safety of yourself and others while on the organisations premises. You must observe the same standards of care and propriety in dealing with patients, staff, visitors, equipment and premises as is expected of any other contract holder and you must act appropriately, responsibly and professionally at all times.

If you have a physical or mental health condition or disability which may affect your research role and which might require special adjustments to your role, if you have not already done so, you must notify your employer and **NHS Tayside** prior to commencing your research role.

You are required to ensure that all information regarding patients or staff remains secure and *strictly confidential* at all times. You must ensure that you understand and comply with the requirements of the NHS Confidentiality Code of Practice and the Data Protection Act 1998. Furthermore you should be aware that under the Act, unauthorised disclosure of information is an offence and such disclosures may lead to prosecution.

You should ensure that, where you are issued with an identity or security card, a bleep number, email or library account, keys or protective clothing, these are returned upon termination of this arrangement. Please also ensure that while on **NHS Tayside** premises you wear your ID badge at all times, or are able to prove your identity if challenged. Please note that the organisation does not accept responsibility for damage to or loss of personal property.

NHS Tayside may revoke this letter and the organisation may terminate your right to attend at any time either by giving seven days' written notice to you or immediately without any notice if you are in breach of any of the terms or conditions described in this letter or if you commit any act that we reasonably consider to amount to serious misconduct or to be disruptive and/or prejudicial to the interests and/or business of the organisation or if you are convicted of any criminal offence. You must not undertake regulated activity if you are barred from such work. If you are barred from working with adults or children this letter of access is immediately terminated. Your employer will immediately withdraw you from undertaking this or any other regulated activity and you MUST stop undertaking any regulated activity immediately.

Your substantive employer is responsible for your conduct during this research project and may in the circumstances described above instigate disciplinary action against you.

No organisation will indemnify you against any liability incurred as a result of any breach of confidentiality or breach of the Data Protection Act 1998. Any breach of the Data Protection Act 1998 may result in legal action against you and/or your substantive employer.

If your current role or involvement in research changes, or any of the information provided in your Research Passport changes, you must inform your employer through their normal procedures. You must also inform your nominated manager and the R&D Office in **NHS Tayside**.

Yours sincerely

Elizabeth Coote
Head of Non-Commercial Research Services

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APPENDIX - C

NHS SCOTLAND

East of Scotland Research Ethics Service *(EoSRES)*

Research Ethics Service

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George Pirie Way
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Dr Gowri Vijay Reesu
PhD Hub-1, Level 8
School of Dentistry
University of Dundee
Park Place
Dundee
DD1 4HR

Date:	10 July 2019
Your Ref:	
Our Ref:	**LR/17/ES/0144**
Enquiries to:	Mrs Lorraine Reilly
Direct Line:	01382 383878
Email:	eosres.tayside@nhs.net

Dear Dr Reesu

Study title:	**Validation of Photographic methods for odontological comparison to aid in human identification**
REC reference:	**17/ES/0144**
Amendment number:	**AM01 (For REC reference only)**
Amendment date:	**24 June 2019**
IRAS project ID:	**236508**

The above amendment was reviewed by the Sub-Committee in correspondence.

Ethical opinion

The members of the Committee taking part in the review gave a favourable ethical opinion of the amendment on the basis described in the notice of amendment form and supporting documentation.

Approved documents

The documents reviewed and approved at the meeting were:

Document	Version	Date
Letters of invitation to participant [2nd Invite HV Clean]	1.0	24 June 2019
Letters of invitation to participant [2nd Invite HV Tracked Changes]	1.0	24 June 2019
Notice of Substantial Amendment (non-CTIMP)	AM01	24 June 2019
Other [Cover email]		28 June 2019
Participant information sheet (PIS) [2nd PIS HV Clean]	1.0	24 June 2019
Participant information sheet (PIS) [2nd PIS HV Tracked Changes]	1.0	24 June 2019
Research protocol or project proposal [Clean]	2.0	24 June 2019
Research protocol or project proposal [Tracked Changes]	2.0	24 June 2019

Membership of the Committee

The members of the Committee who took part in the review are listed on the attached sheet.

Working with NHS Care Organisations

Sponsors should ensure that they notify the R&D office for the relevant NHS care organisation of this amendment in line with the terms detailed in the categorisation email issued by the lead nation for the study.

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

HRA Learning

We are pleased to welcome researchers and research staff to our HRA Learning Events and online learning opportunities– see details at: https://www.hra.nhs.uk/planning-and-improving-research/learning/

17/ES/0144:	Please quote this number on all correspondence

Yours sincerely

L. Reilly

pp
Dr Robert Rea
Chair

E-mail: eosres.tayside@nhs.net

Enclosures: List of names and professions of members who took part in the review

Copy to: TASC
NHS Tayside R&D office

APPENDIX - D

Participant Information Sheet

Title: *"A study of photographic methods to aid in human identification"*

Name of the Researcher: Gowri Vijay Reesu

You are being invited to take part in a research study that will be carried out as part of a PhD in Forensic Dentistry by Gowri Reesu under supervision of Prof. Peter Mossey, Dr. Scheila Manica and Dr. Nathan Brown within School of Dentistry at the University of Dundee. Before you decide whether or not to participate, we need to be sure that you understand firstly why we are doing the study and secondly what it would involve if you agreed to take part. We are therefore providing you with this information. Please take time to read it carefully, ask any questions, and, if you want, discuss it with others. We will do our best to explain and provide any further information you may ask for now or later. You do not have to make an immediate decision.

What is the purpose of the study?

Dental Identification is the most common area in forensic odontology and central to disaster victim identification. When there is no dental documentation, photographs of a (deceased / presumed missing person) smile play an important role. This is an area that has not been explored or utilised to its full potential in human identification. The main purpose of this study is to investigate dental methods for improving the accuracy of human identification using smile photographs, selfies, 3 dimensional digital images of dental models and mouth scans - which provide a high level of detail images of all the surfaces of the teeth and surrounding soft tissues.

What will happen to me if I take part?

You will be asked to sign a consent form to show that you are happy to take part. If there is anything on the consent form, or in this information sheet, that you do not understand or agree with, please tell the investigator before you sign the form. They will be pleased to answer any questions you may have. You will be given a copy of your signed consent form and this information sheet to keep.

Your involvement in the research will be to allow the research investigator to capture your smiling photographs using a digital camera and 3-dimensional camera (4 photographs will be captured from each device - 1 frontal view; 2 left and right views; 1 anterior close up view), also you will be asked to take 5-6 selfies from a mobile device. Later, mouth scans of your teeth will be performed in the orthodontic department. This procedure will take approximately 5-10 mins. Total time may take approximately 20 minutes. The research contribution you make will be anonymous.

The photographs and mouth scans will be carried out on the same day as consenting to the study for convenience, or can arrange to attend at a more convenient time.

Are there any Risks involved?

There would not be any potential risks to the participant as there are no invasive procedures involved. There might be minimal discomfort when performing mouth scans.

Do I have to take part?

It is up to you to decide whether or not to take part. Participation in this study is entirely voluntary and you are free to refuse to take part or to withdraw from the study at any time without having to give a reason.

What if you wish not to participate any further?

You may decide to stop being a part of the research study at any time without explanation. However, we would like to keep any data collected about you up to the point of withdrawal from our research if you agree to that.

What are the possible benefits of taking part?

There is no benefit to you as an individual from taking part in this study but as a token of appreciation for participation, ***each of the participants will be offered an electronic/digital copy of their 3Dimensional facial image on request.*** The potential wider benefits and outcome from the research would be in developing an innovative method to the human dental identification using smile photographs.

Will my personal information be kept confidential?

A unique study number will be allocated to each participant. The data collected do not contain any personal information. For data management purposes, your identifiable information and your anonymised coded study data will also be securely stored on a password-protected database in the University of Dundee. Designated members of the research team will have access to this information. Your data will be archived securely for five years after the end of study, after which it will be destroyed. Identifiable information about you will not be published or otherwise shared.

All Data will be destroyed in the following ways:

Confidential information – cross cut shredded.

Electronic equipment containing information - destroyed using killdisc and for individual folders, they will be permanently deleted from the system and non-recoverable.

What will happen to the results of the research study?

Identifiable information about you will not be published or otherwise shared.

The results of the study may be printed in dental journals, which are read by dentists. The findings may also be presented at conferences where they can be shared with other dentists and researchers. Your name or any other personal details will not appear in any reports about the study as all study data are anonymous.

At the end of the research, when the study results become available, the research investigator will be happy to send a copy of results when the interested participants provide their email address while giving informed consent.

Who is sponsoring the study?

The study is sponsored by the University of Dundee and Tayside Health Board. The study is organized by Prof Peter Mossey.

What if something goes wrong?

If you have any concerns about your participation in the study you have the right to raise your concern with a researcher involved in conducting the study or a doctor involved in your care.

If you have a complaint about your participation in the study, you should first talk to a researcher involved in the study. However, you have the right to raise a formal complaint. You can make a complaint to a senior member of the research team or to the Complaints Officer for NHS Tayside:

Complaints and Feedback Team
NHS Tayside
Ninewells Hospital
Dundee DD1 9SY
Freephone: 0800 027 5507
Email: feedback.tayside@nhs.net

In the event that you think you have suffered harm as a result of your participation in the study there are no automatic financial compensation arrangements. However, you may have the right to make a claim for compensation. Where you wish to make a claim, you should consider seeking independent legal advice but you may have to pay for your legal costs.

Insurance

The University of Dundee and Tayside Health Board are Co-Sponsoring the study. The University of Dundee maintains a policy of public liability insurance which provides legal liability cover in respect of damages, costs and expenses arising out of claims.

Tayside Health Board is a member of the NHS Scotland Clinical Negligence and Other Risks Insurance Scheme (CNORIS) which provides legal liability cover of NHS Tayside in relation to the study.

As the study involves University of Dundee staff undertaking clinical research on NHS Tayside patients, such staff hold honorary contracts with Tayside Health Board which means they will have cover under Tayside’s membership of the CNORIS scheme.

You should be aware that if you apply for health, life, travel or income protection insurance you may be asked questions about your health, including medical history, pre-existing medical conditions, if you have had any genetic test or your participation in this study. It is not anticipated that your involvement in the study will adversely affect your ability to purchase insurance but some insurers may use this information to limit the offer of cover, apply exclusions or increase any premium. If you have a diagnosed medical condition, even where the condition is diagnosed as part of a research study, the insurer may take this in to consideration when deciding whether to offer insurance to you.

Who has reviewed this study?

This study has been reviewed and approved by East of Scotland Research Ethics Services (EoSRES) who are responsible for reviewing research which is conducted in humans and who has raised no objections.

Contact for further information

I will be happy to answer your questions about this study at any time. You may contact me at gvreesu@dundee.ac.uk or 07445386299.

Principal Investigator:
Dr. Gowri Vijay Reesu,
PhD Researcher,

Chief Investigator:
Professor Peter Mossey,
T: 01382 381643
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Academic Supervisor:
Dr. Scheila Manica,
T:01382 38381874
E: s.manica@dundee.ac.uk

Thank you for taking the time to read this information and considering helping with the study.

APPENDIX - E

INFORMED CONSENT FORM

University of Dundee | Participant Identification Number: | NHS Tayside

Title of Study: ***A study of photographic methods to aid in human identification*.**

Name of the Researcher: Prof. Peter Mossey (CI), Gowri Vijay Reesu (Principal Investigator), Dr. Scheila Manica (Academic Supervisor), Dr. Nathan Brown (External Supervisor)

Sponsors: University of Dundee and NHS Tayside

Please initial box

1. I confirm that I have read the information sheet dated.................... (version............) for the above study. I have had the opportunity to consider the information, ask questions and have
had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected. ☐

3. Any data collected about me up to the point of withdrawal from the research will be kept anonymously and used for the research purposes. ☐

4. I understand that data collected during the study, may be looked at by the Researcher and research team, the Sponsors or regulatory authorities where it is relevant to my taking part in this research. I give permission for the Researcher and/or research team, the Sponsors and regulators to have access to my study data. ☐

5. I hereby grant the investigator/photographer permission for photographs, 3D camera and Intra-oral scan images to be taken for this study. ☐

6. I understand that the data collected by the Researcher and research team in this study will be used to support other research in the future, and may be shared anonymously with other researchers collaborating with the Sponsors. ☐

7. I agree to take part in the above study. ☐

____________________	____________________	____________________
Name of Participant (CAPS)	Date	Signature
____________________	____________________	____________________
Name of Person taking consent (CAPS)	Date	Signature

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