A Comparison of the accuracy of three types of 3 dimensional scanners for recording patients' study models and the ease of use of each scanner

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Reference

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This research was undertaken under the auspices of the University of Wales Institute, Cardiff
I hereby declare that this dissertation is the result of my own independent investigation under the supervision of my tutor.

The various sources to which I am indebted are clearly indicated. This dissertation has not been accepted in substance for any other degree, and is not being submitted concurrently for any other degree.

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Abstract

Statement of problem

Dental study models are classed as a patient’s dental record and as a result, they need to be retained for a minimum amount of time for medico-legal purposes. With the ever-increasing dental care, the storage of these models has started to become a problem in dental hospitals, surgeries and laboratories.

Purpose

This thesis will compare three different types of three-dimensional scanners, in terms of accuracy and ease of use to determine whether a three-dimensional scanning technique can be utilised to minimise the problems associated with the current system of storage.

Material and methods

One set of orthodontically trimmed models was selected as a master model and landmarks that utilised flat planes were accurately machined on to each model. Manual measurements were taken using these landmarks and used as a benchmark. The master model was scanned using each scanner and the surfaces acquired were imported into ‘Magics’ were the same measurements were taken. The measurements obtained from each of the scanned surfaces were compared to the manual measurements. A scoring system was developed to aid the assessment of the three scanning techniques.
Results

The analysis revealed that, the manual measurements of the study models were the most reliable. The touch probe scanner was the easiest to use and the most compact. The structured light scanner was the most accurate with all of the average landmark measurements $< \pm 0.5\text{mm}$ to those of the manual measurements, and also produced the surface with the highest quality. The laser scanner performed the best for speed.

Conclusion

Although the scanners demonstrated that the required accuracy and reliability is available, none of the systems were fast enough or at an obtainable price to make them a feasible solution to the problem of study model storage.
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1. Introduction

Dental study models are stone or plaster models which provide a precise, three-dimensional, time-related record of the dental status of an individual and the results that are obtained from the treatment (Ayoub et al, 1997). Ideally, study models should include all of the erupted teeth, the palate, and the full sulcus depth of the patient's oral cavity and they must be trimmed so that both the upper and lower bases are parallel to the occlusal plane (Mitchell, 1996).

Dental study models are often utilised as an important component of the diagnosis, planning and monitoring processes during a patient's dental treatment programme and as a result are classed as a part of a patient's dental record. According to the 1998 data protection act, dental records should be securely stored so that they are not accessible to patients or visitors and safe from disasters such as fire and flood. The BDA states that for medico-legal purposes, dental records (including radiographs and study models) should be retained indefinitely (BDA, 1995). However according to the 1997 Consumers Act, these records should be kept for at least eleven years for adults, and in the case of children, for eleven years or up to age 25, which ever is longest (BDA, 1995). According to the Dental Defence Union (The DDU), in an ideal world, all patients' records should be retained forever (Harvey, 2003). However, it has been acknowledged that this is not always feasible and a more realistic time period must be investigated. The NHS advised minimum period of retention agrees with the 1997 Consumers Act.
However, is it really necessary to retain records for this period of time? In short, the answer is yes and the following case illustrates just how important it is to retain patients’ records.

A patient had been receiving treatment from their long-term dentist before moving away and registering with another surgeon. Fifteen years after the treatment had been completed by the former dentist, an abscess was discovered on the patient’s lower first molar. The patient sought advice from their new dentist who took a radiograph of the problematic area. This revealed that the tooth in question had been root filled and also showed that a piece of endodontic instrument had been left in one of the root canals. The patient’s new dentist removed this tooth and legal advice was taken. A case was put forward stating that the original dentist had failed to remove the fractured segment of the instrument, which in turn caused the loss of the tooth as the patient claimed that they had not been made aware of its presence.

In order to compile a solid defence against this serious allegation, the accused dentist’s records were required to prove that the patient had been correctly informed of the situation. However, these clinical records could not be found. As a result, it was highly likely that the judge would have sided with the patient. Luckily for the dentist, just before the case was due to be settled, the patient’s records were found after a last minute search of the former dentist’s attic. These vital records clearly stated that the patient had been informed of the fracture and confirmed that the patient had declined a referral to an endodontic specialist. Consequently, no further action was taken (Harvey, 2003). This case illustrates that both the NHS and BDA’s recommended guidelines should be treated as the minimum requirement for retaining dental records.
If the dentist in this case study had only retained the patient’s record for the recommended minimum period, the court would have sided with the patient regardless of the dentist being the innocent party. However, it is clear that there is diversity in the recommended time of storage between the different authorities, which is not ideal. There should be one set of guidelines that everyone can follow. Nevertheless, such recommendations have given rise to several problems. The first of these is that study models are very cumbersome and take up a large amount of valuable room in dental hospitals and dental surgeries in relation to normal paper records. Secondly, these study models are often not stored on site in the clinic, which means that retrieving this type of record when required is a time consuming process. Finally, due to the materials that they are most commonly constructed out of, dental study models are fragile and any damage caused to the models will decrease their validity as a record. Regardless of these problems, the retention of dental study models is a necessity and as a result, an alternative method of storage that takes into account the flaws of the current process needs to be developed. With major advances in digital capture techniques over the last 50 years, it is possible that existing three-dimensional scanning methods can be used to provide a suitable alternative.

This thesis will compare three types of three-dimensional scanners by assessing each system in terms of Reliability, Validity, Accuracy and Feasibility. By considering each factor, this study will aim to identify whether or not the technology is readily available at the time of this investigation for this alternative dental study model storage system to be applied as an everyday method in Dental Hospitals, Surgeries and Laboratories. If a scanning system investigated in this thesis can be
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recommended, then it could be utilised to minimise the increasing problems associated with the current system of storage.
2. Literature review

The following text reviews articles relevant to the discipline area. As the area being studied is of a specialist nature, all relevant studies revealed by an extensive search of the literature have been reviewed in this chapter.

This chapter will address what study models are, why so many of them are stored for so long and what alternative methods of storage have been suggested. Since this project will compare three-dimensional digital scanners with a view to using scan data as a method of storage, an explanation of the principles and the use of scanners in dentistry will be discussed. Finally, the literature relating to the arguments put forward for the choice of measurement points will be reviewed. A summary of the sections follows.

2.1 Dental Study Models – Looking at the fabrication of dental study models, factors which affect their accuracy and their function.

2.2 The Reliability, Validity, Accuracy and Feasibility of a storage system. – The definitions of these terms.

2.3 Previous investigations into the storage of study models.

2.4 Three-Dimensional scanners – The basic principles of the three types of three-dimensional scanners.

2.5 Dimensional scanners in Dentistry – The use of three-dimensional scanners in the dental industry.

2.6 Methods of Measurement – Measurement systems used in previous dental research.
2.1 Dental Study Models

As storage of the data held by dental study models is the main feature of this investigation, it is important to understand the role study models play in the dental profession. This section discusses materials from which study models have been fabricated, explains the reasons for the use and storage of study models in dentistry and the legal reasons why they are retained after the treatment has been completed. The implications of this retention are also considered.

Materials used in the fabrication of dental study models

These accurate representations of the patient’s dental anatomy are most commonly constructed out of die stone; a naturally occurring white powdery material (gypsum) is specially treated then mixed with water to form a hard stone-like material. (McCabe and Walls, 1999). However, for experimental purposes other materials have been used in the construction of dental study models. Cohen et al (1995) assessed the dimensional stability of alginate impressions and created a study model out of acrylic resin to use as a master model. Similarly in 2002, Thonthammachat, Moore, Barco, et al also used a non-stone study model when evaluating the factors that influence the accuracy of a study model. However, this time the authors used a model made out of metal as their master model. Although not documented in either of the aforementioned investigations, the main advantage of using study models made from these materials is that they are far more durable than the common gypsum study model. This is evident when comparing the tensile strengths of each material. The strongest form of die stone, Gypsum type 5 has a tensile strength of 9.9 MPa (McCabe and Walls, 1998) compared to that of acrylic at 85 MPa and metal (Cobalt Chromium) at 850 MPa (O’Brien, 1989). Both investigations describe a large sample
of impressions being taken from the master study model, so it was essential that each model remained intact throughout the investigation. Any signs of damage to the master model during the investigation would result in the collection of unreliable results in which case the whole sample would need to be retaken. This is a good method of maintaining the accuracy of the study models throughout the investigation.

**Factors affecting the accuracy of dental study models**

Whilst the crown and bridge field of dentistry requires an accuracy of less than 20 µm (micron) to guarantee a problem free fit (Austin, 2004), dental study models are not required to be as accurate as they are used as a diagnosis aid as opposed to an appliance which fits onto the patients dentition. A majority of previous studies involving dental study models have neglected to place a value on the level of accuracy that dental study models need to meet. Bell *et al* (2003) took a value of 0.5 mm to be significant in their investigation comparing measurements obtained from a three-dimensional scanner to those obtained manually. However details of how this value was obtained were not given.

Factors affecting the accuracy of dental study models will be discussed in the next section.

**Tooth mobility**

Forces, such as those produced during the mastication of food, cause teeth to move in their sockets (Parfitt, 1960). This movement is restricted by the resiliency of the tissues surrounding each tooth.
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Parfitt (1960) investigated the axial movement of a tooth. Axial movements were chosen as these are movements which occur without tilting, so all points on the tooth will move the same amount in the same direction at all times.

A clinically acceptable machine that measured the physiological mobility of teeth was used, giving an accuracy of 0.001 mm ± 7%. Tooth movement was assessed on one individual over a twelve-month period. Although the length of the study allowed a good sample of data to be collected, using a larger sample of people would have generated a more diverse range of results. It is unclear whether the measurements are a general trend that can be applied to all people, or whether they are specific to that one individual. The teeth involved in this study were the right and left lateral and central incisors. Again, including a wider range of teeth would have given a better idea to whether the pre molars and molars moved by a greater or smaller distance. Regardless of these points of criticism, it is evident from the results that the amount of axial movement exhibited by the tooth depended on the type of force exerted on it.

When subjected to forces between 1 gm - 1000 gm, the tooth moved by 0.0004 mm - 0.028 mm. When this force was removed, it was noted that the tooth returned to its original position in two phases. During the first phase, the tooth rapidly recovers part of the distance moved. During the second phase, the tooth slowly recovers back to the original position. The author discovered that when the tooth was exposed to forces at regular intervals such as 2-5 seconds, the tooth does not have sufficient time to complete the second phase and return back to its original position. With each additional application of force, the tooth becomes progressively intruded into its socket, when a continuous forces of 500 gm was placed on the tooth, it was found that
the tooth moved by a regular amount over a period of time (0.002 mm/min). However, a maximum amount was not mentioned by the author.

Parfitt also noticed that tooth movement was dependent of the pre-measurement conditions. When a known force was exerted on the tooth, the gross movement was greatest after a period of sleep or when a night guard, which protected the teeth from intra-oral forces, was worn. This movement was greatest in the morning and decreased as the day progressed. The patient lying down for 10 minutes without any sleep during any part of the day also caused the gross movement to become larger. Parfitt failed to give any quantitative values for these findings, however it is fair to conclude that as the axial mobility of teeth is constantly variable it is difficult to place an exact value on the mobility of a tooth in its socket.

**Stability of die stone**

There are many factors that can affect the dimensional stability of die stone. In an ideal world, dental surgeons would inform the dental laboratory of the type of disinfectant they have used on the impression material. Technicians would cast no more than five impressions at a time using the correct water/powder ratio and the models would be left to set for 24 hours before the impressions were removed. However, this is not the case as a survey carried out by Sharlott *et al* (2000) showed that in a majority of cases none of these factors are met.

Die stones, have a tendency to expand during the setting process. This expansion occurs due to the growth of dihydrate-calcium-sulphate crystals as they precipitate out of solution. The outward movement of the individual crystals results in the increase in
the external dimensions of the dental study cast. Acknowledging this, Millstein (1992) developed a practical method of measuring the distortion of casts made from four common types of die stone – Velmix, Silky Rose, Super Die and Die Keen. Each die stone was used to produce 10 identical models, strictly following the manufacturers instructions. These models were replicas of a stainless steel master model that was part of a measurement system used to determine the accuracy of each duplicate cast. Although there were certain limitations of this measurement system, mainly due to the alignment of the master model with the duplicate, they were recognized by the author. The results of the investigation revealed that there were statistically significant differences between the four types of die stone, with distortions ranging from $0.169 \pm 0.09$ mm to $0.983 \pm 0.06$ mm. The author concluded that cast distortion occurs with all die stones but varies from one type to another.

The incompatibility of impression material can also cause inaccuracies in the final study model. Jarvis and Earnshaw (1980) investigated the effects of alginate impressions on the surface of the dental casts made from gypsum material (an alternative name for die stone). Their literature review revealed that as a general trend, dental casts formed in alginate impressions have relatively poor, chalky and rough surfaces. This affects the accuracy of the dental cast and is a product of incompatibility between the alginate and gypsum materials. In their investigation, authors selected a good range of impression and gypsum materials; however, they failed to mention the grounds on which the different brands of each material were chosen. As a result, it is unknown whether the brands selected for this investigation are the most popular or if they were randomly selected.
The casts were left for 48 hours to set before they were analysed. The results revealed that there was a considerable variation in the compatibility of both materials. A majority of impression materials showed a varying compatibility with the gypsum materials whilst the remaining impression materials produced good uniform surfaces. These findings indicate that Bell et al’s (2003) value of significance of 0.5 mm is a fair estimate.

**Impression material**

The accuracy of impression materials also contributes to slight inaccuracies of the dental study models. The dimensional accuracy of impressions is directly related to the water loss or gain during storage. Figures revealed by Cohen, et al, (1995) illustrate that impressions that are cast immediately produce the most accurate models. However, this is a rare occurrence as impressions are usually packed up and sent to dental laboratory before they are cast. It is here where water loss or gain can occur. Cohen et al (1995) investigated three different types of alginate impressions during five different storage environments (none – immediate casting, 10 minute storage in wet tissue, 1 hour storage in wet tissue, 24 hours storage in wet tissue and 30 minute storage on a bench top) and discovered that the dimensions of the impressions varied by up to 0.68 mm.

The type of material used in obtaining an impression also has an effect on the accuracy of the study model obtained. Peutzfeldt and Asmussen (1989) investigated the accuracy of alginate and elastomeric impression materials and found that all impressions showed an overall net shrinkage. Inaccuracies in the alginate impression
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materials varied between 44 and 188 µm and between 39 and 130 µm in the elastomeric impression materials.

The tolerances in the use of study models currently in existence may be as much as plus or minus 0.5 mm.

The function of dental study models

Dental study models play an important role in dental treatment and as a result, the level of assistance that can be provided by a set of study models should not be overlooked. They can be utilised during the initial stage of treatment, as assistance to diagnosis and treatment planning and during both the intermediate and final stages of treatment, documenting the progress of treatment and results.

Which study models from a course of treatment are produced for each patient depends on the type of treatment he or she is receiving, if at all. For example, a surgeon carrying out orthodontic treatment on a patient would require study models to be constructed more frequently than for a patient receiving regular check ups.

Although not a written rule, McGuiness and Stephens (1991) stressed the importance of standardising the stages of treatment at which study models are obtained, to facilitate clinical audit and research during a period of treatment. They suggested that these times could be

1. Before the start of treatment
2. At the end of active treatment
3. A fixed time out of retention e.g. 6 or 12 months.
Study models can then be used to aid diagnosis and treatment in the following ways.

1. A close inspection of a patient’s study models can make apparent problems such as premature loss, prolonged retention, rotations, individual tooth malpositions, frenum diastemas, muscle attachments and morphology of interdental papillae (Gaber, 1948).

2. Models can be used to perform an accurate space analysis.

3. From an instructional point of view, study models can be used to educate the patient and their family during each stage of the treatment process. Towards the final stage of treatment, they can be used to help the patient decide on how much longer they would like to continue the treatment if given the choice.

4. The effect of each treatment can be illustrated before its initiation by cutting the teeth off the study models and reattaching them to the planned position.

5. They allow the occlusal relationships to be viewed from every angle, which is not possible in the patients’ mouth.

6. Study models give a time related record of the condition of the patients’ teeth and surrounding tissues at a specific time.

7. In some cases, study models may be produced but no treatment is undergone. In these situations, they can be used to reassure the patient that no active intervention is required as the development of the occlusion is occurring satisfactorily (McDonald and Ireland, 1998).

After treatment is complete, study models can be used to monitor the stability of the orthognathic surgery, providing a useful reference to identify unwanted tooth movements. Pre and post treatment models can be utilised to aid audit and quality control whilst the retention of study models is required for medico-legal purposes.
Finally, researchers almost routinely request access to a host of study models for a variety of research topics.

**Methods of Storing of study models**

Dentists treat between 20 and 40 patients a day (Gray, 2005) and whilst not all of these patients require study models many of them do. As a result, the storage of study models has become a major problem. With the amount of orthodontic treatment doubling since the 1990’s (BBC, 2001), specialist practices and hospital clinics require the availability of up to 200 sets of study models each day.

McGuiness and Stephens (1991) investigated the storage of study models in hospital units in the U.K. Although it could be said that the study is limited due to the fact that it only included dentists who worked in a hospital and part time in a private practice, it gives a general idea of the extent of the problem. In the above study a questionnaire was devised to help establish the recommendations and uses of study models by general and teaching hospitals and was distributed to members of the consultant orthodontists group. This proved to be a successful method with one hundred and twenty four out of one hundred and forty seven being returned with all of the participants obtaining study models at the start of the treatment, as they were aware of the importance to do so. The findings clearly showed that most of the participating hospitals were experiencing problems with the storage of study models. Of the participants, 36.3% had a policy of allowing their patients to retain their study models when their treatment was completed. 75.8% had the facilities to store their complete cases in the near vicinity to the hospital unit; however 79% of these 75.8% were experiencing or starting to experience problems with storage. As a result, the mean storage time of study models was 6.44 years, dropping short of the stated desired
average time of 9.75 years and a far cry from today’s advised time of 11 years (Harvey, 2003). From these findings, McGuiness and Stephens (1991) concluded that an alternative method of storing the three-dimensional information obtained from study models should be investigated.

Space is not the only limiting factor in the storage of study models. Dental casts are susceptible to breakage and chipping (Martin et al, 1970). These fragile casts are also bulky and heavy and require storage in boxes or containers. If models are stored away from the hospital unit, then precious time is consumed retrieving these records (Ayoub et al, 1997).

**In summary, this literature shows that**

- Dental study models play an essential part of a patient’s dental record
- A minimum period of retention has been advised by various health authorities and retention over many years is needed
- With increased demand for orthodontic treatment, the storage of dental study models is becoming a problem and an alternative method of storage needs to be addressed urgently.

The following section will explore the meaning of reliability, validity, accuracy and feasibly. These concepts will then be applied to the analysis of the methods of retaining study model data.
2.2 The Reliability, Validity, Accuracy and Feasibility of a storage system.

In the context of this investigation, reliability can be defined as a process that yields the same results on repeated trials. There will always be some degree of unreliable results; however a bias towards consistent results can be referred to as reliable (Carmines et al, 1979). Therefore, if a storage system is not reliable, it can be deemed as useless as there is no guarantee of study models remaining intact or reasonably stable replicas of patients’ dental tissues.

Validity of the data given by a physical study model can usually be taken for granted for practical purposes. All the materials described above have been used successfully by experienced practitioners. However, the validity of a scanning system is an important factor to consider. Coolican (2004) stated that we should be able to have confidence that our measuring device is measuring what it is supposed to measure, in order for the device to be valid. Applying this knowledge, a scanning system should therefore be able to generate data which is relevant to the model being stored and must not be influenced by the areas surrounding it. If a scanning system cannot achieve this then the data produced will not be useful.

Accuracy can be defined as a measurement that is precise and unbiased (Daily and Bourke, 2000). If data produced is not accurate, then any assumptions made from this data will not be 100% true to the model that has been stored. However, a system that does not provide 100% accuracy may still be judged to be accurate for the purposes at hand.
The feasibility of a storage system is the last factor that will be addressed here. This determines the ‘likelihood’ of a storage system being used in everyday practice and takes into account factors such as cost, space and operational training. Each of these factors is as important any other and a useable storage system must sufficiently meet all four criteria. For example, a system that is reliable and accurate but is too expensive, too cumbersome or takes too long is useless.

The next section reviews previous studies that have been carried out into the storage of dental study models.
2.3 Previous investigations into the storage of dental study models

This section will touch upon past research, regarding the storage of study models to help gauge an understanding of previous methods and findings. Where relevant, the advantages and disadvantages of these methods will be identified and used to aid this investigation.

Whilst not all of the following studies are directly related to developing a storage solution for study models, they have aided the understanding of later studies focusing on this problem.

In 1948, Gaber introduced a new microscopic principle that was later referred to as ‘holography’. This study is not directly related to the storage of study models but it is relevant as it provides the basis of future studies referring to the storage of dental study models.

During the same year, Robertson and Kennedy (1948) undertook an investigation to find and develop an accurate and relatively simple method of photography, which could be applied to orthodontic applications. Five different systems of recording photographic data were studied and it was found that Telecentric photography (defined below) was the most reliable and accurate. One of the Robertson and Kennedy’s main aims of their investigation was to see whether this finding was true.

The basic principles of Telecentric photography have been known since the early 18th century and can be described as a system in which an aperture stop is situated at one of the foci of the object lens so that either the entrance or the exit pupil is at infinity
Robertson and Kennedy’s research was initially directed towards the recording of the human face. However, in an attempt to solve the problem of long-term storage of study models, the authors applied the same principles to the photographic recording of study models.

Five sets of study models ranging from Angles class II division I through to class I and II were selected to give a good range. However there was no indication to why a class III representation was not included. Ten clinically acceptable dimensions were taken before and during the treatment, directly from the study models and from the photographs obtained by two different photographic techniques (Normal and Telecentric). The measurements were taken by means of an electronic reading device that was connected to an automatic printer. These measurements were then compared to see which of the two photographic methods achieved the closest results to the direct measurement. However, as no detail was given about the measurement landmarks, it can be assumed that points have been used. The accuracy of these measurements is therefore questionable and repeating such measurements would also be a problem making the system unreliable.

The results of this investigation illustrated that by using Telecentric photography; a greater degree of accuracy can be achieved compared to conventional photography. It was noted that unlike conventional photography, a Telecentric optic system’s accuracy was independent of the positioning of the study model. However, although the storage of study models was not the principal aim of this investigation, the effectiveness of this system as a solution to the problem of the long-term storage of study models was not commented on. Perhaps, therefore, an opportunity was missed.
A flaw of this investigation can be identified by the problems with the use of photography. Photography will only capture a three-dimensional image in a two-dimensional perspective and together with the fact that it is not possible to reconstruct a study model from a photograph makes it less than ideal for referral for legal purposes and past records.

The 1960s brought about the revolution of the common use of holography when Leith and Upatnicks (1965) introduced the use of a laser beam. Their study explored the process of photography by ‘wave front’ reconstruction where instead of recording an image of the object being photographed, the reflected light waves themselves were recorded.

Up to this point in time, there had been many attempts to capture wave front reconstruction, however they were all restricted by the lack of a coherent source of light - light waves that are in phase with one another. This study marked a turning point in the capture of study model data as the introduction of a laser as a source of coherent light made it possible to obtain high quality three-dimensional images.

In 1972 Van Der Linden, et al applied photography to dental casts. They discussed a method that allowed the collection of three-dimensional data whilst treating both the upper and lower casts as one unit.

A microscope mounted over a two dimensionally movable table known as the “Opticom” was the main apparatus used in this method and its sole purpose was to collect information of the dental casts. Whether or not this piece of equipment was commercially available was not commented upon by the authors. A dental cast was
attached to the base and was positioned onto a sliding table, making sure that the point to be recorded was aligned with the centre of two cross wires in the microscope. Data were transmitted from the Opticom through to the Teletype, which types out all the information and punches it to paper tape.

To treat both the upper and lower casts as one, an orientation tower was built. This tower contained two parallel platforms with corresponding precision pins upon which the casts were mounted. The upper cast was adjusted to make the occlusal plane parallel to the base surface. Both casts are then positioned in the lower, with the mandibular cast being brought down into the correct relationship with the maxillary cast.

In order to record the third dimension, the casts were positioned vertically in a slot at the beam, which carried the microscope. The z-axis was then recorded by the use of a pointer that was mounted to a standard base and placed onto the sliding table.

It would take an experienced operator approximately 20 minutes to record one set of casts, which involves 387 measurement points. Although this technique was deemed to be highly accurate, as four individual pieces of equipment were required to carry out the process, it was thought to be cumbersome and expensive (Ayoub et al, 1997).

Problems highlighted in Robertson and Kennedy’s investigations were also apparent in this study. However, a point worth noting is that the study models were captured whilst in occlusion using custom built apparatus. Although treating both the upper and lower models as one unit restricts the view of many areas of each model, the use of a
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custom made apparatus to secure the models is a useful idea preventing any movement during the analysis.

The use of holography as a means of solving the problem of storing and retrieving study models was investigated by Keating et al (1984). In order to understand fully the method used in this study Keating gave a detailed account of the principles of holography, which has been summarised below.

Holography is based on the use of a light. Light is electromagnetic radiation that is a result of the propagation of photons in waves. By looking at the convergence of light, the difference between laser and normal white light can be identified. Normal white light is made up of photons, which possess different wavelengths and frequencies from each other. They are randomly emitted at varying intervals and paths. White light can therefore be called incoherent. Laser light on the other hand is known as coherent. It contains photons that are all emitted at the same wavelength and frequency and all appear from the same direction.

Holography is a wave front reconstruction process in which two coherent beams converge to produce a constructive and destructive interface pattern. One of these beams is reflected by an object, producing a wave front that is unique to that object. Both beams reconstruct at the film, resulting in an interference pattern of the object, which can be identified as the hologram.
Recording a Hologram

A single beam reflection form of holography is used in Keating et al.'s investigation, in which the laser beam first passes through the film as a reference beam and is then reflected back onto the film as an object beam. The film is sandwiched in between two pieces of optical quality glass to ensure that it is kept flat and remains in the same place. The object is placed as close as possible on the other side of the film.

Whilst this process is occurring, it is vital that any kind of vibration does not arise, as this will affect the quality of the image obtained.

Processing

The best results are obtained when films are processed immediately as the image on the film is susceptible to fading within 24 hours.

Films are exposed in semi-darkness similar to the development of standard films. The film is then immersed in a dish of developer with the emulsion side facing upwards. After approximately 45 seconds, the films is removed, rinsed under the tap and immersed in fixer. Finally, it is rinsed again and then dried in methanol.

Image reconstruction

Holograms produced by a white light type reflection do not require the use of a laser beam to be reconstructed. White light will suffice. Once reconstructed, it is possible to obtain accurate three-dimensional measurements from the virtual image. However,
the accuracy can only be guaranteed if the system used for making the hologram is also used for viewing it.

Keating et al. (1984) carried out a pilot study to test the accuracy of the virtual images obtained by use of the method above. Firstly, measurements were taken directly on the study model using a set of vernier callipers in 12 clinically suitable dimensions, ten times. These measurements could be placed into the following groups:

1. Transverse measurements.
2. Arch length.
3. Depth.

The hologram was then reconstructed and these measurements were replicated using the same measuring instrument. All measurements were carried out by one person, a good precaution to take, eliminating possible variation between people’s readings. However, such a measure does suggest that repeatability is a problem. Measurements obtained from the hologram and the physical study models were compared.

The authors concluded that, at the time of this investigation, there was no alternative to address the problem faced by the storage of study models, which would allow three-dimensional measurements to be taken. Other advantages of using holograms are that films can be damaged without spoiling the latent image, whilst the production cost is on par with conventional photography. With the use of a simple cost effective white light source, the latent images can be reconstructed to a clinical standard and
films can be easily stored away with patient’s records allowing easy access when required.

Concerning the archiving of dental study models, the use of holography was a step in the right direction. Unlike photographs, holograms could provide a three-dimensional image from which measurements could be obtained. However, as with photographs, hologram images cannot be used to reproduce physical copies of a patient’s dental cast. As a result, holograms would only be viable as a duplicate, where the original study models were retained and therefore they cannot provide a complete solution to the storage of study models.

Acknowledging that holography could not fully replace the original dental study models, Ayoub et al (1997), introduced the idea of archiving study models in a digital format. A biosterometric technique was used, a technique that is based on the use of stereo pairs of video cameras and a special textured illumination. Any of the areas that were visible to both cameras would be digitally reconstructed. The cameras were connected to a personal computer that was running C3D-Builder, a commercially developed software package. This software required a visible texture in the images in order to produce correct matches, so a fine pattern of random dots was projected on to the surfaces of the models using a slide projector. Once the images were digitized and stored on to the computer, C3D-Builder automatically processed the texture-projected images to produce a three-dimensional reconstruction of the study model.

This preliminary report did not take any formal measurements to measure the accuracy of the computer-generated casts. However, it was estimated that the study
casts were digitised to a precision of about 0.2 mm. The authors neglected the importance of including the method used to assess this degree of accuracy and without it the factors that were taken into consideration during the estimation are unknown. As a result, the overall accuracy of this estimation is questionable.

Ayoub et al (1997) concluded that this newly developed technique would solve the financial implications that are encountered with the mass storage of study models.

The authors stated that their method met the following criteria:

1. By providing an accurate method of storing three-dimensional information that describes dental study casts.
2. By providing an inexpensive method of retaining dental study casts.
3. Data can be stored with patients record files
4. Reconstruction of cast can be achieved with ease
5. Telecommunication between hospitals and practices can be facilitated
6. Records can be superimposed to aid measurement of changes to take place.

Ayoub et al (1997)

Whilst the report suggests that this technique does provide an accurate method of storage for study models, specialist equipment is required to obtain a scanned image of the patient’s dental case. This coupled with the fact that training is necessary to teach staff how to operate the equipment, means that the method described will probably be more expensive than the authors have suggested.

However, the ability to reproduce a dental study model is a definite advantage of this method over previous studies in this field and although a method was not stated by the
authors, it is thought that this process would be compatible with rapid prototyping. The option to store the scanned data with the patient’s file is another benefit, however, in order for the data to be transferred from one hospital to another, each place must possess a copy of the software that is required to view the scanned image. Lastly, another problem that would need to be addressed is the security and backup of the electronically stored data, which was not acknowledged by the authors.

In 2003 Bell et al followed up this investigation focusing on the difference between direct measurements of dental study models with those obtained from computer generated three-dimensional surfaces of the same model, to evaluate the accuracy of Ayoub et al’s (1997) technique. A difference of 0.5 mm between the two sets of data was taken to be significant and a power of 90 was set to ensure that there was a high probability of detecting a significant difference if one was present. No clinical or statistical explanation was given as to why a difference of 0.5 mm was taken to be significant and as such, it is difficult to determine the validity of this comparison. The authors calculated that a minimum of 20 dental study models should be used in this study. However, the lack of information detailing how this number was achieved questions the validity of this decision. Six anatomical dental points were marked on each dental cast and a total number of 15 different measurements were taken from these six points using a vernier calliper, giving a good size data sample. Although the use of a vernier calliper is an accurate method of obtaining a measurement (accurate to 0.02 mm between 0-100 mm) between two landmarks, the use of points is not an accurate method of signifying each landmark. This issue will be further discussed later in this chapter. However, it is worth noting that the same operator was used to carry out all measurements throughout the study, which eliminates the possibility of
variation in measurement due to different operators. However, if a system was to be 100% reliable, then different operators using it should be able to achieve the same results as each other.

The statistical results from this study compared the variation between the eight manual measurements of each point and it was found by the authors that although there were differences between each measurement, none were significant, ranging from 0.10 mm to 0.43 mm. Similarly, the variations between the same measurements made on the three-dimensional surfaces were also insignificant ranging from 0.02 mm to 0.14 mm, although the variation here is lower. More importantly, the differences between measurements made directly on the study model and measurements made on the three-dimensional surfaces ranged between 0.16 mm and 0.38 mm and as a result were not significant. With all of these differences being below 0.5 mm, the authors concluded that the technique introduced by Ayoub et al in 1997 is an accurate method of recording and storing dental study models.

It is worth noting that these two investigations were the first to tackle the problem of the storage of study models using a three-dimensional scanning technique. The success of this investigation illustrates that the use of three-dimensional scanners in this area has been deemed to be a valid technique. The methodology used by the authors has provided a basic knowledge of the general procedures involved in three-dimensional scanning.
Timeline

Figure 2.3.1 illustrates the order at which each investigation took place in history.

- 1948 Gaber Holography first discussed
- 1948 Roberts & Kennedy Photography
- 1960s Leith Development of the laser beam
- 1972 Van der Linden et al. Opticom
- 1984 Keating et al. Holography for storage & retrieval
- 1997 Ayoub et al. Archiving of study models
- 2003 Bell et al. Assessing the accuracy of 3D archiving system

Reviewing this literature has revealed that there have been several attempts to solve the problem posed by the storage of study model data. It has been shown that each solution has its strengths and weaknesses. However, nothing has been published showing evidence that any of these systems have been routinely utilised in practice.

The above discussion has indicated that a three-dimensional digital method of storage would be one of the most advantageous systems. In the current climate, the use of scanners suggests itself. The next section will explain the advantages and disadvantages of three types of available scanner.
2.4 Three-Dimensional Scanners

Three-dimensional scanning is a method of gathering data about an unidentified three-dimensional surface that can be used anywhere there is a requirement to store and/or reproduce a complex shape (Renishaw, 1999). This section will outline the basic principles of different types of three-dimensional scanners. These types of scanners were chosen for review as they fulfilled the criteria of popularity and availability, giving a good representation of the scanners already used in dentistry today.

Structured light 3D scanner

In general, a structured light 3D scanner uses normal white light to capture the three-dimensional geometry of an object and the surface that surrounds it.

The scanner unit is comprised of the following:

1. A projector, which is used to shine horizontal patterns of striped white light on the object
2. A camera, which is used to capture each of the patterns when they appear.

Once the patterns are captured, they are automatically transferred to a PC controller. This runs a unique piece of software that processes the striped patterns and generates a 3D point cloud output, explained below. When the striped white lines are first projected, the lines are both horizontal and parallel. However, upon contact with a surface that is at an angle to the projection, they distort and bend when viewed from various positions. The software on the computer analyses each distortion and calculates the exact position of the surface in 3D space. The scanner repeats this method until a cloud of 3D coordinates has been generated that makes up the object.
being scanned. The result is the object in raw point cloud format, which can then be used to display the overall image.

This form of three-dimensional scanning is deemed to be completely safe because it uses white light and no other form of radiation or laser to capture an object in 3D. As this is a non-contact approach, this system has the advantage of being able to scan soft or fragile objects

**Touch Probe scanner**

A touch probe system utilised a contact technique to gather data of the object being scanned. Firstly, the user defines the area and orientation of the object then a contact probe moves across an unknown surface. As the contact probe follows the objects surface, the scanning system records in the form of numerical position data. The data is then exported in to a CAD/CAM system for further processing. The main advantages of this type of scanning system over a non contact system is that the time consuming processes of manually editing data to remove unwanted points and treatment of surfaces to prevent reflection are not required.

**Laser scanner**

A laser scanner uses laser triangulation to obtain three-dimensional data of an object. A laser light plane is fired from the scanner and deflected by a mirror causing it to sweep across the object being scanned. Upon impact with the object, the laser light is reflected. Each scan line reflected is captured by a digital camera and is used to determine the contour of each surface. This is derived from the shape of the image generated by each reflected scan line. Once all of the required surfaces have been captured, a lattice of points is generated giving a point cloud.
Known advantages of laser scanners are a fast data capture time and no contact to the object is required. The main disadvantage is that due to the nature of the scanner, relying on reflection to generate the data, any object with a highly reflective or transparent surface requires treatment to form an opaque, matte surface before scanning, which is not always possible. As with the structured light scanner, this system has the advantage of being able to scan soft or fragile objects.

This section has given an insight into the basic principles of the three types of scanning system selected for review and covers in the main the types of scanners in common use. The next section will look at how three-dimensional scanning has been applied to other areas of dentistry.
2.5 Three-Dimensional scanners in Dentistry

The use of three-dimensional scanners in the world of dentistry has become increasingly popular over recent years. Not only has it been utilised during the manufacturing process of dental appliances, but also to aid treatment planning and diagnosis. This following section looks at various ways that three-dimensional scanners has been successfully applied in different areas of dentistry.

Orthodontics

The traditional methods of ‘setting a goal’ carrying out a mock surgery can be a very time consuming and laborious process especially when a multi-treatment plan is involved. However, recent research has shown that with the use of three-dimensional scanning, the time for such procedures can be drastically reduced, as it is now possible for this procedure to be simulated using the image produced from the scanned data.

Kuroda, Motohashi, Tominaga et al (1996) developed a three-dimensional cast analysing system that was aimed at doing just that. Using a laser projector measuring device, two video cameras, an image processing unit and a 16-bit personal computer, a dental study model was projected and then scanned with the laser beam. The coordinates of the dental study model were obtained using the image processor and triangulation was applied to reveal the location of each point using the personal computer. Using the three-dimensional images on the computer, measurements of the palatal surface area and volume of the oral cavity could be obtained.
In 1999, Motohushi and Kuroda gave a detailed account of a newly developed three-dimensional computer aided design system that could also aid the diagnosis and treatment planning in orthodontic and orthognathic surgery. The system was made up of a laser scanner, which obtained three-dimensional data of the patient’s study model and a personal computer that gathered the data from the laser to produce a three-dimensional image of the patient’s study model.

The problem met by past studies where blind sectors in the scanned data was an issue, was solved by taking scans of the model from two different directions and merging the data together. This enabled more complex dental anatomy such as cleft palates to be analysed accurately. The proposed tooth movement could also be simulated using this system, where representative planes, marked out by anatomical reference points were located on each tooth allowing them to be positioned to a chosen plane. This was a very useful facility because in orthodontic treatment, the diagnosis and treatment planning stage is particularly important.

**Prosthetics**

Computer aided design (CAD) and Computer aided manufacture (CAM) has been applied in prosthetic dentistry to aid the fabrication of patterns for removable partial denture frameworks. Williams et al (2004) used a structured light scanner to obtain a three-dimensional digital model of a patient’s model. Working on this image uploaded to a computer, the model was electronically surveyed using a mathematical program to identify the undercuts present on the model. A three-dimensional CAD software package was then used to construct the components of the removable partial denture
framework. Once this was completed, a rapid prototyping machine was used to produce a physical plastic shape of the framework designed on the computer.

At this point in time, the disadvantages of this system such as cost of equipment and software plus the experience required to use them are because this type of technology is new in this area. As the technology is explored further, it is possible that procedures such as physical model surveying, blocking out and the ‘waxing up’ of a partial denture framework could become redundant.

**Crown and bridge technology**

The use of scanners in the design and development of crowns and bridges dates back to 1985 when the first crowns were produced by CAD/CAM. Scanning is the first stage of a CAD/CAM process and there are currently several scanning systems available on the market. Procera, one of the most popular CAD/CAM systems on the market, is the only one of these systems to use an analogical probe (‘touch probe’) with a 0.2 mm sapphire pinhead that mechanically reads the surface of the object being scanned. The other systems use either structured light or laser scanners (Duret, 2003).

In 2000, Mömann and Bindl looked at the Cerec 3 system for the production of computer-aided restorations. The Cerec 3 system was developed to simplify and accelerate the production of ceramic inlays, onlays, veneers and crowns.

The main apparatus in the Cerec 3 system is the Cerec scanning unit, which consists of a grinding unit with a laser point sensor mounted onto it. This laser scanner is
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utilised during semi-chair side fabrication of restorations where a dental cast can be scanned three-dimensionally in approximately 5 minutes. The fabrication of restorations can then be carried out on the scan obtained. The advantages of this system lie not only in the time saved but also in the simple nature of the process. This is an improvement over the complicated operational stages of its predecessors. On the whole, the increased flexibility provided by the Cerec 3 system enabled restorations to be fabricated that were otherwise not possible. However, the authors neglected to mention the cost of such a system and with the vast range of hi-tech equipment used the costs are likely to be high, placing it out of reach for mainstream dentistry.

Maxillofacial technology

Hughes, et al (2003), described a technique that could aid the planning process in maxillofacial surgery by utilising computer aided design and management coupled with stereolithographic models. The study involved the fabrication of a custom-made titanium orbital floor prosthesis using everyday maxillofacial laboratory techniques and stereolithographic models. A three-dimensional image of the defective area was obtained using a Siemens Somatom Plus-4 Volume zoom scanner and the data obtained from this process could be used for both three-dimensional imaging and for stereo viewing by the surgeons.

For the next stage, the production of the stereolithographic models, the area required on the scan was selected and the resolution of this selected area was increased to produce a more accurate and natural image. An SLA machine was then used to transform the scanned data into a three-dimensional object by fabricating a model from a liquid resin that cures when exposed to ultraviolet light. The final model
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produced from this process clearly illustrated the defect making its removal easier to assess. Using regular maxillofacial techniques, the prosthesis was constructed on this model.

This section has given a brief insight into the uses of three-dimensional scanning in different areas of dentistry. The following discussion will focus on the various methods of measurements been in past investigations.
2.6 Methods of Measurement

One of the main areas of this investigation requires the development of a suitable system of accurately measuring study models. This section will look at the different measurement systems which have been used in past research, to determine whether a suitable technique or the identification of anatomical points of measurement that could applied to this investigation has already been developed. As already mentioned, research in this area is limited, so methods of measurement used in all areas of dentistry have been reviewed.

Singh and Savara (1964) discovered that a Xerox photocopying machine could be utilised to make prints of dental casts whilst they were investigating new methods for making tooth and dental arch measurements. It was identified that the conventional method of photography required much equipment and elaborate procedures whilst the use of surveyor instruments were thought to be tedious and imprecise. This proposed system would require minimal equipment with easy operation.

Specific landmark points were placed on the buccal cusp tips of the first permanent molars, cusp tips of the cuspids and two points along the palatal midline using black instant lettering. Each dental cast was positioned teeth down on to the glass table of the Xerox photocopying machine and a reproduction was made. To determine if any distortion or magnification in any dimension would be present, a Xerox print of a 25 by 20 cm graph paper was made. Length, width and angular measurements were taken from this print and it was evident that no enlargement would occur if the casts were placed within the middle 10 cm of the glass table.
The following measurements were taken manually from a random selection of 10 dental casts to determine the accuracy of the reproduction. Each cast was measured twice independently.

1. The Arch Length – from the mesioincisal edge of the left central incisor to the distobuccal cusp tip on the left first permanent molar.

2. The Intercuspid Width at cusp tip.

3. The Intermolar Width at the distobuccal cusp tips of the first permanent molars.

Two Xerox prints were then made for every cast on which the same measurements were obtained on each print independently. The results gained from this investigation illustrated that the difference in the measurements obtained from the Xerox prints and the dental casts, were not significantly different.

Utilising a technique such as this would not only be simple, but also an accurate and time saving means of gathering specific measurements using minimal equipment. The use of black instant lettering to appoint the measuring points on to the model was a good idea as it made it possible to remove these measuring points with ease, leaving no damage to the cast. However, a landmark of this nature would not be suitable for the present project as a touch probe scanner would not be able to identify the black lettering. Another potential problem with the use of black instant lettering is that it would be difficult to ensure that the measurement is taken from that exact marking every time. This technique only required measurements to be taken on a single plane,
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dismissing the possibility of analysing the buccal and labial aspects of the arch or indeed any measurements in a vertical direction.

Yamashita et al (1996) developed a three-dimensional measuring system based on the theory of gradient method, using a fixed CCD TV camera, mobile vertically scanning projectors and a computer. This theory was not defined in the paper so the exact method is unknown.

The mobile projectors were used to manoeuvre around the object, illuminating each of its surfaces in a grid like pattern. Recordings were made of the brightness at a certain point on the surface of the object according to the motion of the illuminated pattern. The object was then deformed and the point brightness was taken again using the same method. A lateral curve was obtained and plotted on the same graph with that obtained before the deformation, allowing the results from each object to be compared. The accuracy of this measuring system was tested using an apparatus composed of a micro gauge and two white blocks used to replicate an object.

The two blocks could be adjusted to vary the difference in height between each other simulating an object before and after deformation. With the height difference adjusted to zero, an area measuring 30 x 15 was analysed. The height difference was then varied between 100 μm and 1000 μm and the same area analysed. The computer was used to summarise the data gathered and it was found that the deviation of error varied from ±10 μm at 100 μm to ±30 μm at 1000 μm deformation. As a result, Yamashita et al concluded that this system could be widely used within the dental field. However, this method may have a limited appeal, as it will only take measurements in a vertical plane.
From the point of view of this thesis, a limitation of both Singh and Savara (1964) and Yamashita et al's (1996) techniques is that they are restricted by the fact that they compare physical objects to one another and not a physical object to a digitally scanned image on a computer. This can be regarded as a point of criticism as it is an aspect of the physical world which is being recorded for storage. Such a comparison plays a major role in this study.

A point worth noting is that each of these investigations used a method to test the accuracy of their measuring devices, which in turn allowed them to find the best position to achieve the most accurate measurement. Similar studies would do well to take such measures.

**Using anatomical features**

Alemda, Phillips, Kula et al (1995) studied the possibility of using the palatal rugae as reference points to develop the reference planes necessary for longitudinal cast analysis. One of their main aims was to determine whether the positions of the palatal rugae were stable during normal growth. A graphite pencil was used to carefully mark the palatal raphe and the most medial and lateral end point of the palatal rugae. One operator marked the casts whilst another checked the location of these landmarks. The landmark was denoted as missing if there was any doubt of its location. The landmarks were then digitized, using an optical plotter known as a Reflex Metrograph by the operator who marked the cast (the availability of this instrument was not given in the text). These digitized co ordinates of the landmarks were used to construct a median palatal plane (MPP) on the palatal raphe allowing the following measurements to be taken.
1. The perpendicular distances from the MPP to the ruga.

2. The transverse linear distances between medial points and between lateral points of the right and left rugae

3. The left and right anteroposterior linear distance between medial and between lateral points of the first, second and third rugae.

Alemida et al (1995) found that minimum training was needed to achieve results with low errors, using the Reflex Metrograph to locate and read the points. However, eyestrain was a problem and rest intervals were required. It was concluded that the medial ruga proved to be suitable anatomical points for use as reference landmarks.

The problem with applying this technique to the use of scanners is that the landmarks marked by pencil would not be picked up by a touch probe scanner. A modification to this technique could solve this in the form of a small hole, groove or flat plane, however the palatal ruga is too small to consider this. This technique will also only allow measurements to be taken on an x and y-axis.

Kojima, Sohmura, Nagao, et al (2003) attempted to develop a plane that was defined by landmarks on soft tissue, for use during three-dimensional analysis of dental casts, to solve the problem of establishing an occlusal plane on patients with a malocclusion. The top of the maxillary tubercles and the top of the incisal papilla were chosen as reference landmarks (Figure 2.6.1) because accurate impressions of these areas could be easily obtained.

The plane that was formed by these landmarks ran from the maxillary bilateral tubercles to the top of the incisal papilla and was referred to as the MTIP plane. The
angles that were formed by the MTIP plane and the occlusal plane were analysed on the sagittal and frontal plane (Figure 2.6.2). The occlusal plane was defined by the mid point of the mesial angles of the right and left central incisors and the distobuccal cusp tips of the upper first molars on both sides. A stable plane could be established by using these soft tissue characteristics as landmarks. However, there are possible issues with using these landmarks with regards to the collection of measurements. It would be difficult to take measurements from such landmarks due to the irregularity of their surfaces.

Nevertheless, the idea of using an artificial plane to take measurements from is a useful technique. By establishing a known measuring surface, measurements made from this surface to another will be more accurate than measurements made from two unknown surfaces.

![Figure 2.6.1](image1.png)
Maxillary tubercles and the incisal papilla. I: Incisive papilla, R: maxillary right tubercle, L: maxillary left tubercle

![Figure 2.6.2](image2.png)
Angles formed by the occlusal plane and the MTIP plane. (a) On the sagittal plane, (b) on the frontal plane

(Kojima et al, 2003)
Bell et al (2003) chose six anatomical dental points on each dental cast as landmarks, to help assess the accuracy of a three-dimensional imaging system. The Euclidean Distance Matrix Analysis together with an Orthomax Vernier calliper, a digital measuring device, was used to measure the linear distances between each point. However the authors failed to define the Euclidean Distance Matrix Analysis so it is difficult to understand the exact method they used and as a result, the accuracy of this measurement system cannot be determined.

A total of 15 measurements were made on each cast (Figure 2.6.3) with each point being measured eight times. The models were scanned twice. One image was taken under normal illumination and the other under projection, and then digitally stored on a computer. These images were then superimposed to allow the measurement points placed on the casts to be visualised. A computer automated measuring tool was used to carry out the same measurements that had been carried manually with the Orthomax Vernier calliper, the average distances in measurements made on the 3D images, and the actual study models were compared.

Details of how these points were selected together with how they are placed on the study models were not given. However, closer inspection of Figure 2.6.4 shows that, they may have been applied with a pen. Again, this is a measuring point that would not be picked up by a touch probe scanner and may not provide a high degree of accuracy. The latter point will be taken up in a later section.
The authors’ use of a vernier gauge to measure between points on the dental anatomy gives evidence that this piece of equipment is accurate enough in obtaining measurements on dental study models from small measurement landmarks. In addition, the frequency of the manual measurements taken for each distance may sound excessive, but repetition of these measurements helps generate a good sample of data from which any anomalies can be easily spotted and eliminated. Bell et al’s investigation demonstrates that the anatomical alignment of teeth can be looked at as a starting point for creating reference landmarks on dental casts for three-dimensional assessments.

The dental arch has traditionally been divided into three segments. Segment A is a curved line that follows the coronal plane, extending across the midline from canine to canine. It describes the anterior segment. Segment B is a straight line, extending from the distal edge of the canines to the mesiobuccal cusps of the first molars. It describes the middle segment.

Segment C is also a straight line and extends from the mesiobuccal cusps of the first molars backwards to the mesiobuccal cusp of the wisdom tooth. (Berkovitz et al, 1978) The points generated by the boundaries of each segment could be used as
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reference points for measurements. However, one problem is that these suggested landmarks would only be useful as reference points on a single plane. It would therefore not be possible to determine whether the dimension of the dental cast has altered or not, in a three-dimensional scan.

Perhaps the major down fall of these four investigations is that they require measurements to be taken from a single point over and over again, which will be difficult to replicate accurately due to the following reasons:

1. It would be very difficult to ensure that the measurement is taken from the exact point every time in different systems. For example, when a scan is acquired and viewed on the computer, it will be difficult to determine the correct position of the point to replicate the physical measurement taken. This has led to the common practice of having a single person take measurements in the studies cited above and the concomitant doubts about reproducibility.

2. Using points on a study model as a measurement landmark would only be suitable for laser and light scanners. A touch probe scanner would not be able to identify the point being used as the landmark, which means there would be no points to take measurements from when the scan is viewed on the computer.

3. Another problem with measuring from point to point, is that it is possible to end up with an overall distance that incorporates components of distances x, y
and z. This is known as a three-dimensional vector and can lead to errors. It is accepted that measuring across planes is more accurate (Figure 2.6.5).

![Diagram showing measuring from plane to plane and point to point.](image)

**Figure 2.6.5** One of the many problems of measuring from point to point.

From reviewing these studies, it is clear that a measurement system that takes into account the following principles has yet to be developed.

- A method of creating measurement landmarks appropriately so that they can be used with laser, light and touch probe scanners.
- A method to ensure that measurements can be taken from these landmarks repeatedly.
- A method that allows measurements to be taken in more than two planes, i.e. three-dimensional measurements.

The following section summaries the topics discussed in this chapter.
2.7 Summary

This chapter has reviewed a wide range of literature to aid the development of this investigation. In doing so, the uses of dental study models have been identified and previous investigations regarding the storage of these models have been looked at. Although research into alternative methods of retaining study models can be traced back to the mid 20th century, it was not until recent years that a suitable system has been established which depends essentially on scanners.

Reviewing the use of three-dimensional scanners in different areas of dentistry illustrated that the use of this technology has already been recognised in this field. The three-dimensional scanners reviewed are the three most available types at the time of this investigation.

Finally, various systems of measurements relevant to dental casts were considered and although none were found to be suitable, reviewing this literature has aided the understanding of the type of measurement system required for investigation. The next chapter describes and discusses several methods, which take these principles into account.
3. Method and Materials

This chapter will document the methods used to obtain the results in this investigation. The previous chapter reviewed past literature relevant to this study. Ideas from these studies have been built upon and used in the development of the following methods.

3.1 Obtaining the master set of dental study models.
3.2 Devising landmarks.
3.3 Choosing landmarks.
3.4 Milling of the landmarks.
3.5 Obtaining physical measurements of the dental study models.
3.6 Three-Dimensional Scanning - The Structured light scan.
   - The Touch Probe scan
   - The Laser scan.
3.7 Obtaining measurements from the scanned data.
3.8 Devising a scoring system to aid the assessment of the three scanning methods.
3.9 Methods of analysis.

3.1 Obtaining the master set of dental study models

Dental study models were required for this investigation. A set of orthodontically trimmed models was selected from several available at the Centre for Dental Technology, University of Wales Institute Cardiff. The models were originally of patients but the anonymity has been preserved, indeed probably lost. All models present were made out of die stone, as it is a known fact that this type of material experiences the least problems related to dimensional change for dental purposes. To further diminish any problems relating to the dimensional stability of the study
models, all models present were approximately 2 years old. At this age, any dimensional changes due to chemical reactions would have almost certainly already occurred.

All models from the sample were carefully inspected for any discrepancies such as chips and air inclusions and the best set of models was selected (Figure 3.1.1).

![Figure 3.1.1 Set of study models chosen for this investigation. A) In occlusion. B) The occlusal surfaces.](image)

The use of models made out of a more robust material such as metal or resin were considered by Cohen, *et al* (1995) and Thonhthammachat, *et al* (2002). However, although such materials have the advantage of being more durable, Gypsum type 5 has a tensile strength of 9.9 MPa (McCabe and Walls, 1998) compared to that of...
acrylic at 85 MPa and metal (Cobalt Chromium) at 850 MPa (O’Brien, 1989), in reality study models are most commonly constructed out of die stone. A sample of models made from this material would generate results more applicable to those used in everyday practise.

A set of study models, comprising of an upper and lower as opposed to just a single upper or lower was not only chosen to generate more data but also to simulate a real situation as dental study models are usually needed in pairs. Another reason for this decision was to enable the occlusion of the models to be assessed in image form.

Storage of Dental Study Models

The set of Dental Study Models was stored in a cardboard box used for this purpose. A piece of foam was placed in between the upper and the lower casts, which were held together in occlusion with an elastic band.

Care was always taken when models were being used, as it was important to use the same set throughout this investigation. The use of duplicate models of the original was ruled out as it was felt that this could contribute to slight inaccuracies in the results. Extreme care was therefore needed because if the chosen models were broken during any point of this investigation, all data collection would have to be repeated. Each study model was carefully cleaned using soap and cotton wool before each scan.
3.2 Devising Landmarks

An accurate system of taking measurements on both physical and digital study models was required for this investigation. As noted in Chapter 2, previous studies had utilised points as landmarks, which is not the most accurate way of obtaining measurements.

With no suitable landmarks available from previous research, a suggestion from staff from a commercial three-dimensional scanning company was considered.

The commercial company had previously been working on a landmark system, which could be used to take measurements of a dental cast once a scan had been obtained.

The general idea was to position three spheres in the palate of each study model, allowing digital measurements to be taken from different planes.

The problem that was identified with this system was that whilst it worked well for scan data, for manual measurements it did not provide good measurement facilities.

It would be difficult to use a measurement instrument such as a vernier gauge to measure from a sphere repeatedly as it only gives curved points point from which to measure.

It was initially thought that this idea could be modified to solve the issue by using a flat-sided object such as an upside down pyramid. This would give five flat planes from which to take measurements, doing away with measuring from points, whilst maintaining the ability to take measurements from different planes. However, measurements would still be taken from the flat planes to points. Other problems with this system are that inverted pyramids in the palate would create an obstruction during the scanning process and a touch probe scanner would experience difficulties scanning such landmarks as these scanners can only measure minute undercuts.
Another possible site of measurement that was suggested was to utilise the flat planes given by the seven sides of the study models base. The main advantage of this idea was that the study model would not have to be modified in any way. Measurements of the study model could be taken from one side to any of the remaining sides of the study model’s base (Figure 3.2.1)

![Figure 3.2.1 Possible measurements using the seven sides of the base.](image)

However, the problems with this method were that the measurements were too simplified and not fully relevant, as they did not take into account any measurements of the anatomical area of the study model. Finally, measurements would only be taken from one plane and it would also be difficult to manually obtain these measurements on the physical model, as although the planes are flat, they are not parallel to each other.

**Final landmarks**

Building on the above considerations, flat parallel planes were chosen to represent the landmarks as multiple measurements could be taken more conveniently. The use of these planes eliminated the inaccuracies possible from measuring between specific
points. When repeating measurements between two points, each reading had to be strictly taken from an exact point on that feature, allowing inaccuracies when these points are not correctly identified. Measurements between two parallel flat planes could be made anywhere on these features eliminating the potential risk of this problem as illustrated in figure 3.2.2. Flat, parallel planes allow several attempts at measurement at different sites. Thus, a mean and standard deviation can be arrived at and greater confidence can be achieved than by taking a single, point-to-point measurement.

![Diagram of measurements between two flat parallel planes]

**Figure 3.2.2 Measurements between two flat parallel planes**

In software terms, specific points are hard to locate and subsequently hard to measure from as there are thousands of them present in a point cloud. Flat planes on the other hand can be readily identified from the general trend in a point cloud. When measuring between features that are knowingly parallel to each other, any deviations from the normal value can be put down as inaccuracies in the scan. It is for this reason that measurements in this research will always be taken from at least one known parallel plane.
In terms of obtaining manual measurements of the study model, measuring from plane to plane allows better access to the landmarks for the measurement equipment involved in this investigation.
3.3 Chosen landmarks

The following landmarks were chosen as they gave a combination of the biggest distances likely to be measured on a dental cast, a variation of measurements and were in similar positions to the dental anatomy.

Upper Dental Cast - Patient’s Left

Figure 3.3.1 Back datum to Incisor

Figure 3.3.2 Back datum to Molar
Figures 3.3.3 and 3.3.4 illustrate measurements on an upper dental cast. Figure 3.3.3 shows the base datum to top of molar, while Figure 3.3.4 demonstrates the back datum to incisor.
Figure 3.3.5 Back datum to Molar

Figure 3.3.6 Base datum to top of molar plane
Lower Dental Cast - Patient’s Left

Figure 3.3.7 Across arch (Molar – Molar)

Figure 3.3.8 Back datum to Incisor
Figure 3.3.9 Back datum to Molar

Figure 3.3.10 Base datum to top of molar
Lower Dental Cast - Patient’s right

Figure 3.3.11 Back datum to Incisor

Figure 3.3.12 Back datum to Molar
Figure 3.3.13 Base datum to top of molar plane

Figure 3.3.14 Across arch (Molar – Molar)
3.4 The Milling of the Landmarks

Before this investigation, a tried and tested method of milling flat planes on dental study models was not documented. As a result, a pilot study was carried out to find a suitable method of creating the required landmarks. The first attempt described immediately below was improved upon at a later stage.

A Cendres & Métaux SA PFG100 Paralleloemeter was used to mill a flat plane on to the occlusal surface of the first molars of an upper arch. A magnet was attached to the base of the model via a plaster base, making sure that the plaster was extended over the base onto the sides of the model to allow for retention without scoring the model. Adding a plaster base also helped elevate the model, allowing it to be positioned within the milling arm’s reach. The magnet table was attached to the paralleloemeter and the model was placed on to it.

The surfaces of the first molars were milled flat using a 3 mm milling attachment. Milling continued until all of the fissures had been eliminated, leaving a flat plane. The milling arm was then lowered by 2 mm and an attempt to mill out a cross through the centre of both first molars was made.

Once completed, the distances across arch between the first molars from these landmarks were measured. With use of a vernier gauge, measurement was taken from the mesial aspect of both teeth and then repeated from the distal aspects of both teeth. A difference in the results showed that the milled crosses were not parallel to one another, so a second attempt was made on the second molars. This time the crosses were marked out onto the flat planes before milling. The centre of the patient’s right
molar was approximated and a cross was drawn through the centre of the tooth (figure 3.4.1). To obtain a cross on the patient’s left molar that ran parallel to the one on the right, a measurement was taken from the mesial aspect of the right molar, point A to roughly the centre of the mesial aspect of the left molar, point A1. Point B1 was then obtained by measurement of the distance between points A and A1 from point B. Points A1 and B1 were joined up to give a line which ran parallel to line A-B. Next, line C1 - D1 was obtained by lining up a ruler with line C-D and continuing the line across the arch (figure 3.4.2). These crosses were lined up with the cross that ran along the magnet table.

The following problems with this method were highlighted.

1. The positioning of the magnet table on the Paralleloometer is accomplished by eye making it difficult to position the table perfectly horizontal.

2. It was difficult to ensure that the milled lines were parallel to one another, which is essential for accurate, reliable measuring.

The result of this pilot illustrated that a more accurate method of milling was required to create the landmarks.
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An engineer’s Universal Milling Machine was chosen to create the required flat planes on the study models (Figure 3.4.3). The nature of the milling machine meant that it would be simpler to ensure that the planes were milled to the exact specification.

Figure 3.4.3 Universal Milling Machine

The upper study model was positioned onto a 25 mm MDF block that acted as a sacrificial baseboard. Vinyl double-sided adhesive tape was used to attach the study model to the sacrificial baseboard due its ability to fasten two objects strongly together whilst at the same time being easy to remove cleanly.
The study model was clamped into position at (A), using two parallel bars, which not only brought its overall height within comfortable reach of the milling arm, but also insured that the study model was sitting on a level surface.

A 12 mm slot drill was placed into the chuck of the milling machine (B) and milling of the back plane was carefully undertaken. Once the back of the model was parallel to the drill piece, the drilling arm was raised and moved into position to begin the milling of the flat plane on the labial aspect of the central incisors. Care was taken to ensure that these teeth were not made too thin and milling was stopped as soon as a flat plane that was sufficient to take measurements from was achieved.

Next, the milling arm (C) was raised over and positioned above one of the first molars. An attempt to mill the surface of the molar flat so that it was parallel to the base of the study model was made. However, a problem arose when the tooth started to chip away in random areas. It was thought that this was due to the drill piece being too big, so the 12 mm slot drill was replaced with a 3.5 mm long reach slot drill. This change solved the problem and together with this, the following technique was also employed to help minimise the possibility of the tooth chipping. A milling depth of 2 mm was chosen and the gauge on the height adjustment wheel (D) set to zero. Milling commenced, starting from the buccal aspect of the tooth, working towards the middle. Once this half was eliminated, the milling arm was raised over the remaining half and then lowered so that the gauge on the height adjustment wheel was back to zero. This ensured that the milling depth remained at 2 mm. Milling commenced, starting from the mesial aspect of the tooth working towards the middle. Once the bulk of the tooth was removed, the surface was inspected for any remaining fissure indentations. If any
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were still present, the milling arm was lowered in 0.5 mm increments and run over the surface until they were all removed. This technique was then repeated on the remaining first molar.

Next, a 2 mm slot drill was used to mill the planes required across the now flat first molars. A path was chosen across the arch from one first molar to another, which would run approximately through the middle of both teeth. This was accomplished by moving the milling arm in the direction of the required path whilst the drill was not rotating. The milling arm was set to give a depth of 1.5 mm and milling was undertaken at a slow speed.

Finally, the mesial-distal plane was milled on both first molars. This was positioned approximately in the midline. Again, the machine-path was chosen by moving the milling arm in the direction of the required plane. This plane was extended so that it just ran on to the neighbouring teeth (distally on the second premolar and mesially on the second molar). This ensured that there would be no rounded edge present on the area of the plane from where measurements may be taken.

The study model was then unclamped and the planes were inspected to determine whether they ran parallel to one another by measuring the distances between them with a digital vernier gauge and the milled planes were verified as parallel. The sacrificial baseboard was carefully removed from the study model and this whole process was repeated on the lower model.
Once the landmarks had been milled on both models, the next stage was to obtain physical measurement of the models. These measurements were taken using the following equipment.

1. A Surface Table. Figure 3.5.1 shows the surface table used in this study. The basic ideal of a surface table is that the surface of the table is at an exact horizontal plane. Therefore, any object placed onto this surface will be on a perfectly even surface.

A self-contained height and scribing instrument (see figure 3.5.2) was placed onto the surface table and calibrated so that the surface of the table was at zero.
2. A digital vernier gauge calliper (Figure 3.5.6). An accurate measurement device made up of a digital gauge with a graduated bar and a sliding jaw bearing a short scale.

Each measurement was repeated 4 times by the same operator and an average was taken. Overall, seven different measurements were taken four times on each cast, giving a total of 56 results.

**The Back Datum – Central incisors measurement**

This measurement was taken using the surface table. The model was placed onto the surface table with the back datum on the table (Figure 3.5.3). The height-measuring instrument was then lowered until contact was made with the surface of the incisors where a reading was taken.
**The Back Datum – first molar measurement**

This measurement was taken using the surface table. As with the previous measurement, the model was positioned on to the surface table with the back datum on the table. The height instrument was lowered until contact was made with the surface of the measurement plane on the molar. A reading was then taken. (Figure 3.5.4)

![Figure 3.5.4 Tip of measuring device meeting flat plane on the first molar](image)

**The Base Datum to first molar measurement**

This was the final measurement taken using the surface table. The model was placed on to the surface table with the base datum on the table (Figure 3.5.5). The measurement instrument was lowered until contact was made with the measurement plane on the first molar where a reading was taken.

![Figure 3.5.5 Tip of measuring device meeting flat plane on the top surface of the first molar](image)
The across arch measurement

This measurement was taken using the set of vernier gauge callipers, as it was easier to access the measurement planes with this instrument as opposed to the surface table. The callipers were slowly opened until the measurement planes on both first molars were reached where a reading was then taken.

Figure 3.5.6 Digital Vernier gauge calliper

The models were sufficiently prepared at this stage to allow scanning to begin. This is discussed in the next section.
3.6 Three-Dimensional scanning

Three types of three-dimensional scanners were chosen for this investigation. Each scanner and its software were used to obtain three-dimensional images of the master study models. The output images were saved in a Standard Triangulation Language (STL) file format, a standard format used for rapid prototyping.

<table>
<thead>
<tr>
<th>SCANNER TYPE</th>
<th>MODEL NAME</th>
<th>SOFTWARE</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURED LIGHT</td>
<td>Steinbichler Comet 250</td>
<td>InnovMetric Polyworks - IMAlign</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alias - Wavefront Spider</td>
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<tr>
<td>TOUCH PROBE</td>
<td>Renishaw Cyclone</td>
<td>Tracecut</td>
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<tr>
<td>LASER</td>
<td>Minolta Vivid 900</td>
<td>Tower graphics - Easy 3D scan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INUS Technology - Rapidform 2004</td>
</tr>
</tbody>
</table>

Table 3.6.1 Scanners and their software

Each output file was then imported into 'Materialise’s Magics’ a Rapid Prototype production, inspection and preparation software where all the required measurements were acquired.

**Structured light scan**

The method used in this study to obtain a structured white light scan can be broken down in to three stages.

1. Scanning the object
2. Aligning the data
3. Polygonising

1. **Scanning the object**

A Steinbichler Comet 250 white light digitiser was used to obtain a scan of the study models. The study models were cleaned and placed in occlusion on a black table and the scanner aimed. A black table was used so that the surface of the table would not
be included in the scan. The positioning of the study models on the black table was determined by an infrared light that was emitted from the scanner. This allowed the model to be positioned in the path of site of the scanner’s lenses. The initial scan was taken with the models in occlusion to allow the upper and lower completed scans to be positioned into the correct occlusion.

One scan took approximately 40 seconds upon which a point cloud of the scanned area was generated on the computer screen. The lower study model was removed from the black table and scanning of the upper study model commenced (Figure 3.6.1). As the nature of a structured light scanner meant that only the surfaces of the study model that were in the “line of sight” were captured, multiple scans were needed to ensure that all the required surfaces of the study models were described. This process was repeated for the lower model.

![Figure 3.6.1 Position of scanner in relation to black table.](image)

2. Aligning the data

Following each individual scan, the data collected was added to the collection of data obtained from previous scans, building up an overall scan of all the required surfaces of the study model. To ensure that an accurate representation of each surface was
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obtained, the entire geometry of each individual scan was aligned to each other using InnovMetric Polyworks IMAlign, a point cloud inspection and reverse engineering software. IMAlign enabled two point clouds to be imported and aligned to each other using the following process.

a. The point cloud of the first surface was imported into IMAlign and locked into place. This initial point cloud determined the positioning of all point clouds to follow.

b. Next, the point cloud of the following scan was imported into a new window in IMAlign. (Figure 3.6.2)

c. Using the N-Point pairs alignment tool, three to five points of commonality between the two scans were selected on each cast.

d. A rough alignment of the two point clouds followed by an accurate alignment using a least squares algorithm was then performed by right clicking the mouse.

e. Once the alignment of all required surfaces was complete, all of the scans were selected and the Select Unique Data function was utilised. This function selected all of the points apart from the points that made up overlaps in the scanned data.

f. Next a function which added a very small amount of overlapping data to the selected points, the Grow 5 function was applied to ensure that no gaps were left in the overall point cloud.

g. Finally, the selected areas were inverted. The unwanted data was now selected rather than the best data, which allowed the unwanted data to be deleted.
Figure 3.6.2 Alignment of two point clouds. Left Image – Collection of previous scans already aligned. Right Image – Newly acquired scan. Please note although images seem to have a surface and point clouds, it is only a view option to make the alignment process easier.

3. Polygonising

For the final stage, the point cloud data was imported in Alias Wavefront’s Spider software. This package was used to join up all of the dots present in the point cloud creating a polygon mesh. A simple explanation of this would be to visualise thousands of dots in space representing an object. To the naked eye, these dots mean nothing. However, if a thin piece of cloth was pulled tightly over these dots, from an outside position, surfaces would be created revealing an object. This process produces an STL (Standard Triangulation Language) file, which is more universally recognised than point cloud files.
Problems with scanning milled cross landmarks

A problem was identified when the data generated by the first structured white light scan was polygonised and the image was viewed. To help understand the cause of the problem, it is important to note the definition of the two following terms.

Vertex tolerance

Controls how closely the verticals must match the original points. If a low value is set then more polygons will be used to describe the surface, as there will be vertices joining up more of the original points. This results in a denser mesh.

Grouping tolerance

Controls how close points must be for the program to consider them part of the same mesh.

(Definitions taken from Alias - Wavefront Spider software)
Using Alias Wavefront's Spider, a point cloud and polygon manipulation package, a 0.015 mm computer estimated grouping tolerance was used in an attempt to generate the best image possible. However, the image produced, as shown in figure 3.6.3 shows that even though this generated a good replication of the majority of the cast, the landmark crosses were not fully duplicated. This is a result of there not being enough points to plot out this vital part of the dental cast.

To counter this problem, the grouping tolerance was increased to 2 mm and the result can be seen in figure 3.6.4. Initially, the image generated looks to be sufficient and the landmark crosses can now be seen clearly. However, as a result of increasing the grouping tolerance, points generated from the noise outside the model have now been included in the final image. The telltale signs are the random spikes that protrude from the dental cast and upon closer inspection, it looks like the computer has assumed the bases of the crosses. The low number of points in this area, together with the high grouping tolerance selected, makes it impossible for 'Spider' to ascertain which points describe the surface and which points are noise. Therefore, although a surface has been generated, the accuracy of this surface is highly questionable, as the surfaces do not appear as flat as they are on the physical cast.
Cause of inaccurate surfaces

A combination of the nature of the equipment and the dimensions of the landmarks is the cause of the unsatisfactory image shown in figure 3.6.2. The structured light scanner used to acquire these scans uses two separate lenses. Lens number one is a projector lens that projects a fringe pattern on to the object, which in this case is the dental cast. Lens number two is essentially a digital camera that captures the projected pattern of light on the surface of the dental cast. In a successful scan, the path of both the projected light and the digital camera should eventually meet up at the area that is being scanned, point X in figure 3.6.5. If this path is obstructed in anyway, a scanned image of that area will not be obtained.
Figure 3.6.5 illustrates one of the lenses being obstructed by the edge of the tooth. Subsequently data of the base of the cross cannot be obtained, resulting in the lack of points in that area of the scan.

A solution to this problem

The causes of this problem were carefully considered in order to find a suitable solution. Using a different scanner was out of the question as this is the general nature of all structured white light scanners. This meant that the structure of the landmark needed to be addressed.

A simple solution was established which involved the re-milling of the landmark tooth to remove three of the four sides of the cross as shown in figure 3.6.6.
This left two flat planes which were sufficient from which to take all of the required measurements, whilst not obstructing the path of the two lenses from the structured light scanner in any direction.
**The Touch Probe scan**

Renishaw’s Cyclone Touch Probe scanner and Tracecut scanning software were used for this part of the investigation. A single dental cast was attached to a metal spacer using a hot glue gun.

A Z-plane was established by using the flat areas on the dental cast, which allowed the probe to work in a parallel plane. This was done to cancel out any inaccuracies of gluing the cast to the spacer, and this represented the Z datum 0.0. The back plane of the dental cast was aligned by the vertical probe ensuring the cast was square to the axes of the machine. The X and Y planes were determined by locating a common ground on either side of the dental cast and finding the centre of these two points. Each datum represented point 0.

A star shaped stylus with 1 mm sphere ends was chosen for the digitising process (Figure 3.6.7). Data of the top surfaces to half way down the dental cast were taken using the vertical pointing Z probe. The remaining surfaces were digitised using one of the four horizontal X Y probes and each probe was calibrated for its length to allow the model to blend correctly.
The next stage involved obtaining a two-dimensional profile from the occlusal surface to the gingival margins using the vertical probe to ensure that the path the probe took was within the area required. Once this had been carried out, the scanning process was initiated. This whole procedure was repeated for the opposing dental cast and scanning of each cast took approximately ten hours from start to finish.

The next stage involved the conversion of the raw data collected from the scans into an STL file format. This was done by selecting the CAD output menu in the Tracecut software menu and clicking on STL. The area of the data required for the conversion was inputted using the x and y values before the start of the conversion. This procedure took half a minute for each cast.

The main problem encountered during this processes was due to the use of the star shaped stylus. The positioning and length of each probe had to be carefully considered to prevent one probe from obstructing the measurement of another.
The Laser scan

A Minolta Vivid 900 non-contact three-dimensional laser scanner was used for this part of the investigation. The method used to obtain the final three-dimensional images can be broken down into two stages:

1. Scanning
2. Merging of images.

1. Scanning

The general nature of this type of scanner meant that not all the surfaces of the study model could be scanned with the study model situated in one position. As a result, both the upper and lower models were captured in two separate scans: one capturing the occlusal and palatal surfaces (model placed on its back plane) and one to capture the remaining surfaces of the models (model placed on its base plane).

Scanning of the upper study model was undertaken first. The upper study model was placed base down on to a rotary stage controller. This device is essentially a turntable used to rotate the study model during the scan. It was important to ensure that the model was placed directly on the centre of the rotary stage; otherwise, the model will not remain on the same axis during the 360° rotation. ‘Blu Tack’ was used to secure the model to the stage once the position had been established.

Tower graphics’ ‘Easy 3D Scan’ software was used to control the scanner and the rotary stage. Once opened, the scanners view of the study model could be visualised. Adjustments to the height and tilt angle of the scanner and its distance from the study
model were made to ensure that the study model was within the focal point (marked by a cross on the computer screen) of the scanner and that the image of the study model fitted within the viewing area of the software. Auto-focus was implemented, and the rotary stage was set to stop at every 60° giving a total of six images per scan. A detail level of 500 was selected. These values were chosen as a previous study (Keating, 2004) has shown that this combination gives a good compromise between detail and file size.

The scanning process was then initiated and an initial scan was taken to calibrate the scanner. This was followed by the real scan. Once the scan was completed, ‘Easy 3D Scan’ pieced all six images together and simplified the data, removing any duplicate polygons and reducing the number of unnecessary polygons from the base to reduce the file size. It is possible to do this without losing detail. As the surface was known to be flat, a high number of polygons were not required. The image generated from this first scan illustrated that many of the sulcus regions of the study model had not been captured. It was evident that the scanner was experiencing problems capturing these areas due to the positioning of the model. A wedge shaped block was positioned and secured to the centre of the rotary stage to give the study model a 20° tilt, anterior facing up towards the scanner. This allowed the scanner better access to the areas in question (Figure 3.6.8).

This procedure was repeated, until all of the required surfaces had been captured. Next, the upper study model was placed back down directly onto the centre of the rotary stage. The equipment was re adjusted to suit the new position of the study model and a scan was initiated.
Figure 3.6.8 Wedge shaped block to give model a 20° angle towards the scanner

A problem was identified upon completion of this first scan. ‘Easy 3D Scan’ experienced problems whilst piecing the six images together. As the edges of the base are straight, there are minimal landmarks for the software to snap each image to. The result was that that the edges were not accurate. To solve this problem, artificial landmarks were created on the edges of the study models using rolls of ‘Blu tack’ (Figure. 3.6.9)

Figure 3.6.9 ‘Blu Tack’ on edges of base to aid scanning software
Scanning of the lower model was achieved using the same method used on the upper. A 15° wedge shaped block was used as opposed to a 20° block as it gave the scanner a better view of the study model.

Finally, the upper and lower study model was placed into occlusion and held in position with two strips of ‘Blu Tack’ placed at the rear of the models. The same method used above was then repeated to obtain the required images.

2. Merging of images.
RapidForm 2004 was the software used to merge the separate images taken from each rotation together to form one complete three-dimensional image of the upper and lower study model.

a. The six images collected from the first scan of the upper study model were imported in to RapidForm 2004.

b. Small shells generated by noise in the air and marks on the surrounding surfaces were removed

c. The second set of six images from the second scan of the upper study model were imported in to RapidForm 2004

d. Small shells were removed

e. Both images were then aligned to the same plane

f. Six points were selected on the first image and then these same points were selected on the second image

g. The register button was selected which roughly lines the two images together using these six points.

h. If the two images were lined up sufficiently the images were merged together permanently. Any overlapping data was deleted. If the images
are not lined up correctly, then stage g should be repeated ensuring that
the six points are selected more accurately on both images

i. The image was then smoothed and any remaining unwanted shells
were removed

j. Stages c to i were then repeated until the images from all scans were
imported and merged together.

k. This procedure was then repeated for the lower study model.
3.7 Obtaining Measurements from scanned data

Measurements of the scanned images obtained from each scanner were carried out on a computer using ‘Magics’ by ‘Materialise’ Magics is a Rapid Prototype production, inspection and preparation software that is specifically designed for reading STL files. It enables different forms of measurement to be taken, such as from a point to a point (the simplest form) or from a plane to a point. The latter of the two was chosen for this investigation. By measuring from plane to point, one plane is used as the start point and then measurements are taken at several different points on the opposite plane. This provides several slightly different measurements, which indicates the variation in the measured plane. For example, if both measurement planes were perfectly straight and perfectly flat then the perpendicular distance from one plane to any point on the other would always be exactly the same.

An STL file produced by one of the three scanners was imported into Magics. The measuring tool was selected and used to obtain the exact same measurements taken on the physical models (see Landmarks of this chapter). To aid this process, each area of measurement was magnified until the triangles representing the surfaces of the images were visible (Figure 3.6.10).
Figure 3.6.10 Triangles visible on the surfaces of scanned image

To obtain a measurement between two landmarks, for example A and B, a point was selected at A and then at B using the measurement tool. The measurement tool snaps to a vertex of a triangle nearest to the points selected and displays the distance between them. As measurements were always taken from one known parallel landmark, Magics obtains a point from this plane and then calculates the tolerance of the data generated by the vertexes of triangles forming the surface of the other landmark to obtain two points on the planes from which to take a measurement.

As with the manual measurements, each measurement was repeated four times and an average was taken. The standard deviation of these measurements was also recorded. This procedure was repeated for the remaining two STL files from the other scanners.
3.8 Devising a scoring system to aid the assessment of the three scanning methods

As there was no evidence of previous work discussing comparisons between different three-dimensional scanning systems for use in the storage of dental study models, criteria were developed to aid this evaluation. The accuracy, feasibility and validity of each system were assessed by taking into account the six factors listed below. For each system, a rating between 1 and 5 is awarded for each factor where 5 is ideal and 1 is poor. Half ratings can be awarded if the result of the scanning method falls in between the specified criteria. Once a system has received a rating for all the factors, the ratings are totalled to give an overall score.

The manual measurements obtained have been regarded as the base line of comparison as they are expected to be more accurate than the measurements obtained from the scanned data. The reason for this is that the manual measurements are taken directly from the model whilst for each scanning system the measurements are acquired from the scanned data, where there is a high possibility that there are missing areas of the study models within the scanned data.

1. Ease of use

The ease of use was judged by the amount of training, if any, that was required to fully operate the scanning system. As all three scanning systems require the use of a personal computer, this factor also takes into account the level of computer skill that was required by the operator. A system that requires little training and computer background will score higher then a system that requires vast training and advanced computer knowledge.
<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use</td>
<td>No training required. Users will be competent to operate the equipment by trial and error. Beginner computer skills are required.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Minimal Training required. Users will be competent in operating the equipment after a simple training session. Beginner computer skills are required.</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Training required. Users will be competent to operate the equipment after a couple of training sessions. Intermediate computer skills required.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>A training course is required to operate the equipment. Users will be able to acquire skills required to operate the scanner and piece together the data obtained to produce a surface. Intermediate computer skills are required.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>An intensive training course is required to operate the equipment. The users must possess advanced computer skills to operate the scanner and piece together the data obtained to produce a surface.</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.8.1 Scoring index – Ease of use criteria

2. Accuracy

The accuracy of the scanning method is determined by how close the measurements of the landmarks on the scanned images are to the manual measurements. Factors such as tooth mobility in their sockets - a maximum of 0.03 mm (Parfitt, 1960), the dimensional stability of impression material - up to 0.68 mm variation (Cohen et al 1995)) and the expansion of die stone - 0.05-0.15% (O’Brien and Ryge, 1978) suggest that an acceptable tolerance value for scanner accuracy is justified. Agreeing with the findings of Bell et al (2003), a difference of < ±0.5 mm between the average results for each
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landmark compared to that of the scanning method has been taken to be not
significant. The number of times a difference of $< \pm 0.5$ mm is achieved is
placed over the number of landmarks – 14.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>14/14</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10/14</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>7/14</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4/14</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1/14</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.8.2 Scoring index – Accuracy criteria

3. Scanned data quality

As detailed in section 3.9 of this thesis, the anatomy of the surfaces produced
by the data acquired from each scanning method was assessed to determine
which of the three scanning methods produced the most realistic impression of
the master models. The percentage of data coverage, surface condition and
topology of the surfaces were all taken into account in this assessment.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scanned data quality</td>
<td>Surface produced from the scan has a percentage of data coverage of 100%, with no signs of noise or rippling in the data. All landmarks have been visually reproduced, with the overall surface giving a good representation of the models scanned.</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Surface produced from the scan has a percentage of data</td>
<td>4</td>
</tr>
<tr>
<td>Factor</td>
<td>Criteria</td>
<td>Rating</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Time – Operator time</strong></td>
<td>An operator is required for:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 - 59 minutes</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>60 – 119 minutes</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>120 – 179 minutes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>180 – 239 minutes</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>240 – 299 minutes</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.8.4 Scoring index – time criteria – Operator time

The second set of criteria focuses on the time taken for the whole scanning process required to obtain a scan and generate a three-dimensional surface of one study model. A time scale of between 10 minutes and >10 hours has been created for this criteria and although the time gaps are not proportional to the ratings they have been created by taking into account the actual times taken by each scanner in this investigation. The less time required generating and saving the image, the higher the rating.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time – Overall time</strong></td>
<td>Models can be scanned and a surface obtained on the computer screen for each study model.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 10 minutes</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>&lt; 60 minutes</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>&lt; 300 minutes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>&lt; 600 minutes</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>&gt; 600 minutes</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.8.5 Scoring index – time criteria – Overall time
5. Space

This paper has already revealed that space for storage is a major concern especially in dental hospitals, so ideally the less space a scanning system requires, the better. Being able to move the scanning system when required without too much trouble is also another advantage, as is a system that does not require a specific location, such as a dedicated dark room. Methods which require a large amount of space, a dedicated room and which uses equipment which cannot be easily moved will achieve a low rating.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>All necessary equipment takes up no more room than a standard PC and accessories and does not require a special location. (Can be moved if required).</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>All necessary equipment takes up no more room than a standard PC and accessories but requires a specific location. (Can be moved if required).</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>All necessary equipment takes up more room than a standard PC and accessories but can be easily packed away when not required.</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>All necessary equipment takes up more room than a standard PC and accessories. Equipment can be removed when not required but this is a lengthy process.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>All necessary equipment requires its own dedicated room.</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.8.6 Scoring index – Space criteria
3.9 Methods of Analysis

This section details the methods that have been used to analyse a comparison of the measurements of each system results from this current investigation. The Co-efficient Variance Ratio and Student t Test were run on the results obtained and each scanning system was scored using the criteria developed for this investigation (section 3.8).

Scanned Data Quality

The anatomy of the surfaces produced by the data acquired from each scanning method was assessed using the following criteria to determine which of the three scanning methods produced the most realistic impression of the master models.

1. **Percentage of data coverage** – the percentage of data coverage was calculated from information given in the Magics software. For each surface, the number of ‘bad edges’ and ‘bad clusters’ was identified (Figure 3.9.1). The smaller the number was for each field the closer the data coverage was to 100%. As the data from the structured light scanner is a finite bound volume, i.e. the number of ‘bad edges’ and ‘bad clusters’ for the data obtained was 0, the surface obtained using this method can be said to have 100% data coverage.
The following calculation was used to determine the percentage of coverage for the remaining two methods.

For upper surfaces:

\[
\frac{\text{Surface area of upper scan from method}}{\text{Surface area of upper scan from structured light scanner}} \times 100
\]

For lower surfaces:

\[
\frac{\text{Surface area of lower scan from method}}{\text{Surface area of lower scan from structured light scanner}} \times 100
\]

This calculation will highlight any gaps present in the data.

2. **Surface condition** – The condition of the surface, noting features such as ‘noise’, ‘pits’ and ‘fuzziness’.

3. **Topology** – The general shape of the surface looking at how closely the surface resembles the master model and whether it has retained detailed features such as undercuts and the landmarks.
Time Scale

The time taken for the complete scanning process for each scanning method was recorded. As not all three types of scanners require the exact same process, four generic stages have been formulated so that a comparison of the time-span can be easily made between each scanner. These generic stages are the following:

1. **Preparation period** – The time taken to prepare the models (e.g. spray surface of models white), calibrate scanner and surrounding environment (e.g. light) and warm up scanner.

2. **Data acquisition** – Time taken for the scanner to acquire data of the model.

3. **Obtaining a point cloud** – Time taken to merge scans, align and tidy up data.

4. **Exporting to an STL format** – Time taken to convert the data obtained from the scanners into a universal STL file format.

The times given for each stage are in minutes and are for each study model.
**Statistical analysis**

The following statistical tests were used to aid the analysis of the measurements achieved from each scanned surface. All calculation was carried using Microsoft Excel.

**Standard deviation**

Standard deviation is a measure of the dispersion or variation in a distribution of data and was used in this study to calculate the variance ratio co-efficient.

**Co-efficient variance ratio (C.V.)**

The co-efficient variance ratio is a calculation of the relative measures of standard deviation and is used to compare the consistency or variability of two or more series.

\[
\text{C.V.} = \frac{\text{Standard deviation}}{\text{Mean}} \times 100
\]

Expressed as a percentage, the higher the variability, the higher the C.V. and vice versa. The C.V. has been applied in this study for the following purposes:

1. Within landmarks to compare the variability present in the repeated measurements for each landmark across each method. Appendix i
2. Across landmarks to compare the variability across the mean measurements for each method. Appendix ii.

**Student t Test**

The student t test calculates whether there is a real difference between the means of two samples of data. It was used in this study to determine whether the variations in the results between each scanning method and the manual method were significantly different. A p value of <0.05 was taken to be significant. The statistical results from
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each scanner were compared to that of the manual method in order to compare each of these novel alternatives with current practice

The average result from each set of measurement for each landmark was used when comparing the measurements obtained from a three-dimensional scanner method to the manual measurements. This stage was carried out in Microsoft Excel 2003 using the following formula:

\[ =t \text{TEST}(X1:X13,Y1:Y13,2,1) \]

A two-tailed related t Test was selected which gave the P value (appendix ii). A two-tailed t test was chosen because it was not predicted that one measurement would be bigger then the other. After the analysis was complete, all the data were passed on to a colleague to enter into SPSS in order to obtain the T values (appendix iii).
3.10 Summary

This chapter gave detailed accounts of the methods used in this investigation starting with the selection of the sample study models. Previous studies were reviewed in the last chapter and ideas were noted from these investigations and used in the development of a suitable measurement system for this study. Manual measurements were then taken using these landmarks on the study model.

Transferring the required landmarks to the study model required the experimentation of several methods before a suitable method was established. These landmarks were put to the test during the first scanning session and problems with certain landmarks became apparent. The landmarks in question were modified to solve these problems, and scanning of the study models was undertaken using the 3 different scanners. Measurements were taken of the scanned data generated by scanners and each set of measurements will be looked at in comparison to the physical model in the next chapter.

The absence of criteria to assess three-dimensional scanners was identified so one was developed to aid the comparison between each scanning method. The final section of this chapter explained the statistical tests used on the results of this investigation.
4. Results

This chapter will display and describe the range of measurements obtained from the physical measurement of the upper and lower study models. As mentioned in the previous chapter, each study model contained seven different possible sets of measurements. Each measurement was repeated four times, giving a total number of 28 measurements for each study model. With there being two study models, an upper and a lower, an overall total of 56 measurements were taken for each method. For each scanning system, the quality of the scanned data will be assessed. A picture of the upper and lower study model scans for each scanning method has been selected at angles that best represent the surfaces achieved. The time scale will be looked at next followed by an assessment of the measurements obtained, reviewing the outcome of the statistical tests. Finally, the results of the scoring index will be revealed. However, it is necessary to start by looking at the results of the manual measurements.

4.1 Manual measurements of the Master Study Models

Measurements

There are no signs of anomalies in the 56 measurements manually obtained. This is clearly illustrated by standard deviation values ranging from 0.00 – 0.02 mm. The highest variation between a set of four measurements was observed along the patient’s right Back-Molar landmark of the upper study model and the Base-Molar landmark of the lower study model, again on the patient’s right.

The lowest variation was seen along the patient’s left Back-Incisor landmark on the upper study model and the Back-Molar landmark on the lower study model of the patient’s right where the measurements were consistent throughout each set.
Table 4.1.1 Upper study model for manual measurements

Patient’s Left

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td>1 2 3 4</td>
<td>Ave</td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td>52.87 52.87</td>
<td>52.87</td>
<td>0.00</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>22.46 22.45</td>
<td>22.45</td>
<td>0.01</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>28.10 28.11</td>
<td>28.11</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Patient’s Right

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td>1 2 3 4</td>
<td>Ave</td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td>52.9 52.88</td>
<td>52.91</td>
<td>0.01</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>22.39 22.36</td>
<td>22.34</td>
<td>0.02</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>28.11 28.12</td>
<td>28.11</td>
<td>0.01</td>
</tr>
</tbody>
</table>

| Across arch   | 43.16 43.14| 43.16 | 43.15 | 0.01 |

Table 4.1.2 Lower study model for manual measurements

Patient’s Left

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td>1 2 3 4</td>
<td>Ave</td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td>48.23 48.22</td>
<td>48.21</td>
<td>0.01</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>24.36 24.35</td>
<td>24.35</td>
<td>0.01</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>24.3 24.29</td>
<td>24.3</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Patient’s Right

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td>1 2 3 4</td>
<td>Ave</td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td>48.23 48.25</td>
<td>48.23</td>
<td>0.01</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>24.36 24.37</td>
<td>24.37</td>
<td>0.00</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>24.26 24.28</td>
<td>24.26</td>
<td>0.02</td>
</tr>
</tbody>
</table>

| Across arch   | 41.07 41.05| 41.06 | 41.06 | 0.01 |
Statistical analysis

The Co-efficient variation ratio

Overall, the majority of the C.V obtained for each of the sets of measurements was the lowest obtained for each landmark across the methods. The lowest C.V. was zero and this was obtained on the upper left back-incisor landmark whilst the highest C.V. of 0.11 was observed on the upper right back-molar landmark. The average C.V. for the upper and lower sets of measurements was 0.03. (Also see appendices i and ii)

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Upper Patients’ left</th>
<th>Upper Patients’ right</th>
<th>Lower Patients’ left</th>
<th>Lower Patients’ right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-incisor</td>
<td></td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Back-molar</td>
<td>0.03</td>
<td>0.11</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Base-molar</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Across arch</td>
<td>0.02</td>
<td></td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.03</td>
<td></td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1.3 C.V. values for manual measurements
4.2 Structured light scanner

Scanned Data Quality

![Figure 4.2.1 Structured light - Upper Cast](image1)
![Figure 4.2.2 Structured light - Lower Cast](image2)

**Percentage of data coverage**

As noted in section 3.9, both the upper and lower scanned surfaces have data coverage of 100%. This is visually evident in figures 4.2.1 and 4.2.2 where there is no evidence of gaps on the surface.

**Surface condition**

Overall, the surface of the anatomy on both the upper and lower study models was good. Closer inspection reveals a slightly rippled effect present, however this is mostly evident on the gingival and palatal regions of the models. A minimal amount of noise in the data can be seen around the periphery of the anatomy, which has given a fuzzy texture around these areas. A small amount of pitting is apparent on the horizontal flat surfaces of the first molars.
Topology

The data from the structured light scan has generated a good representation of anatomy of both the upper and lower study models. All landmarks are present, however corners that are meant to be at right angles appear to have been slightly rounded off. This can be seen on the landmarks on both sets of first molars.

Time Scale

The preparation period of the structured light scan entailed making sure the models were as clean as possible (5 minutes) and warming up the scanner lamp (10 minutes), however these two processes were carried out concurrently. Finally, the scanner’s light and brightness settings were calibrated which took a further 5 minutes.

Data were acquired in approximately 30 minutes for a single model and approximately 60 minutes was required to align and merge the multiple scans and reduce noise to obtain a point cloud.

The point cloud data took approximately 30 minutes to be polygonised and exported as an STL file.

<table>
<thead>
<tr>
<th>Process</th>
<th>Time taken (Mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation period</td>
<td>15</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>30</td>
</tr>
<tr>
<td>Obtaining a point cloud</td>
<td>60</td>
</tr>
<tr>
<td>Exporting to an STL format</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>135</strong></td>
</tr>
</tbody>
</table>

Table 4.2.1 Time taken for each process of the structured light scan
Measurements

All 28 measurements were obtained successfully on both the upper and lower study models using this method. There are no anomalies as such, however the across arch landmark ranged between 42.67 mm and 42.99 mm on the upper study model and between 40.9 mm and 41.23 mm on the lower study model. This generated a standard deviation value of 0.14 mm on both sets of results.

In comparison, the remaining sets of measurements are more uniform, giving standard deviations ranging between 0 – 0.05 mm

Table 4.2.2 Upper study model for structured light scanner

Patient’s Left

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Landmark</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td>53.18</td>
<td>53.14</td>
<td>53.17</td>
<td>53.14</td>
<td>53.16</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Back - Molar</td>
<td>22.67</td>
<td>22.73</td>
<td>22.66</td>
<td>22.63</td>
<td>22.67</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Base - Molar</td>
<td>28.19</td>
<td>28.19</td>
<td>28.2</td>
<td>28.18</td>
<td>28.19</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

Patient’s Right

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Landmark</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td>53.15</td>
<td>53.15</td>
<td>53.14</td>
<td>53.13</td>
<td>53.14</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Back - Molar</td>
<td>22.48</td>
<td>22.56</td>
<td>22.59</td>
<td>22.52</td>
<td>22.54</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Base - Molar</td>
<td>28.17</td>
<td>28.18</td>
<td>28.18</td>
<td>28.17</td>
<td>28.18</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

 Across arch 42.67 | 42.99 | 42.9 | 42.87 | 42.86 | 0.14 |
Table 4.2.3 Lower study model for structured light scanner

Patient’s Left

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td></td>
<td>48.68</td>
<td>48.68</td>
<td>48.68</td>
<td>48.68</td>
<td>48.68</td>
<td>0.00</td>
</tr>
<tr>
<td>Back - Molar</td>
<td></td>
<td>24.72</td>
<td>24.72</td>
<td>24.73</td>
<td>24.73</td>
<td>24.73</td>
<td>0.01</td>
</tr>
<tr>
<td>Base - Molar</td>
<td></td>
<td>24.33</td>
<td>24.31</td>
<td>24.32</td>
<td>24.33</td>
<td>24.32</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Patient’s Right

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td></td>
<td>48.66</td>
<td>48.66</td>
<td>48.69</td>
<td>48.70</td>
<td>48.69</td>
<td>0.01</td>
</tr>
<tr>
<td>Back - Molar</td>
<td></td>
<td>24.86</td>
<td>24.76</td>
<td>24.80</td>
<td>24.74</td>
<td>24.79</td>
<td>0.05</td>
</tr>
<tr>
<td>Base - Molar</td>
<td></td>
<td>24.50</td>
<td>24.52</td>
<td>24.53</td>
<td>24.51</td>
<td>24.52</td>
<td>0.01</td>
</tr>
</tbody>
</table>

| Across arch    |             | 41   | 41.04 | 41.23 | 40.90 | 41.04 | 0.14  |

**Statistical analysis**

**The Co-efficient variation ratio**

**Within landmarks**

Whilst an average C.V. of 0.12 for the upper sets and 0.10 for the lower sets are higher than that of the manual measurements, there are several times where the C.V for these two methods have been the same. This is evident on the following landmarks: Upper left base-molar, upper right back-incisor and lower left back-molar (appendix i). A lower C.V. than the manual method was achieved a further four times on the upper right base-molar landmarks and the lower left back-incisor lower right back-incisor and finally the lower right base-molar landmarks (appendix i).

The higher C.V. average compared to the manual method can be accounted for by five results, which are considerably higher than the results obtained by the manual measurements for the given landmark (appendix i). The lowest C.V obtained was zero
for the lower left back-incisor landmark and the highest C.V. obtained was 0.34 for the lower across arch landmark (appendix i).

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Upper</th>
<th></th>
<th>Lower</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patients' left</td>
<td>Patients' right</td>
<td>Patients' left</td>
<td>Patients' right</td>
</tr>
<tr>
<td>Back-incisor</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Back-molar</td>
<td>0.18</td>
<td>0.21</td>
<td>0.02</td>
<td>0.21</td>
</tr>
<tr>
<td>Base-molar</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Across arch</td>
<td>0.31</td>
<td></td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.12</td>
<td></td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2.4 C.V. Values for within landmarks for structured light scanner

Across landmarks

The result from the C.V. test carried out on the mean measurement for all of the measurements shows that the mean measurement for the structured light scanner varied very slightly less than that of the manual method (appendix ii).

**Student t Test**

The general trend observed was that the mean measurements obtained for the structured light scanners were a fraction higher than the manual method (appendix 2.01). Indeed this difference in the measurements from the structured light scanner compared to the manual method was significant, \((t=3.49 \ df=13, \ p<0.05)\) (appendix iii).
Francis Alimohamed

4.3 Touch Probe Scanner

The commercial company’s first attempt at scanning study models only allowed the across arch landmark to be taken on both arches, giving a total number of four measurements on each arch. Details can be found in the appendix iv.

On the commercial company’s second attempt, all 28 measurements were obtained on each arch.

Scanned Data Quality

Percentage of data coverage

Upper surface

\[
\frac{10984 \text{ mm}^2}{12741 \text{ mm}^2} \times 100 = 86\%
\]

Lower surface

\[
\frac{10424 \text{ mm}^2}{12338 \text{ mm}^2} \times 100 = 84\%
\]
The percentage of data cover was 86% for the upper and 84% for the lower. Figures 4.3.1 and 4.3.2 give no evidence to expect values such as these as there are no obvious gaps in the data. As there were no undercuts present in the scan, a surface area larger than that of the structured light scans was expected.

**Surface condition**

Figures 4.3.1 and 4.3.2 clearly illustrate that the condition of the surfaces for both models is very poor. The buccal and labial surfaces of the upper anatomy and the labial and palatal surfaces of the lower anatomy suffer from severely jagged surfaces. Again there is a small amount of pitting present on the horizontal surfaces of the first molars on both models; however there is no evidence of any noise in the data.

**Topology**

The data from the touch probe scan has not given a good representation of either study model. No undercuts are present on the models. The labial and buccal aspect of the upper anteriors and posteriors have no detail, which is also true of the labial aspect of the anteriors and palatal aspect of the posteriors on the lower.

Whilst all of the landmarks are present on both models, they are not particularly clear especially on the centrals. The vertical surfaces of the landmarks on the first molars are on roughly a 45° angle to the horizontal surface on the molars.

**Time Scale**

The preparation period lasted approximately three minutes in which the cast was secured to a metal spacer and a datum capture was acquired. Once the machine was
Francis Alimohamed

setup the cast was left for approximately ten hours where data of the study model was obtained.

One minute was required for a point cloud to be obtained and saving the data to an STL format took approximately 1 hour.

<table>
<thead>
<tr>
<th>Process</th>
<th>Time taken (Mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation period</td>
<td>3</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>600</td>
</tr>
<tr>
<td>Obtaining a point cloud</td>
<td>1</td>
</tr>
<tr>
<td>Exporting to an STL format</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>664</strong></td>
</tr>
</tbody>
</table>

Table 4.3.1 Time taken for each process of the touch probe scans

**Measurements**

There were no obvious anomalies present in the data. However, the standard deviations of both arches show that the data in each set varied a great deal in most cases. The biggest deviation is evident on the Across Arch Measurement of the of the upper study model. Here, measurements varied from 43.31 mm to 43.61 mm.

Measurements of the patient’s left and right Base-molar landmark of the upper study model and the patient’s left Base-molar landmark of the lower study model showed the least deviation of 0.01 mm.
Table 4.3.2 Upper study model for touch probe scanner

Patient’s Left

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td></td>
<td>52.85</td>
<td>52.76</td>
<td>52.74</td>
<td>52.82</td>
<td>52.79</td>
<td>0.05</td>
</tr>
<tr>
<td>Back - Molar</td>
<td></td>
<td>22.38</td>
<td>22.45</td>
<td>22.38</td>
<td>22.58</td>
<td>22.45</td>
<td>0.09</td>
</tr>
<tr>
<td>Base - Molar</td>
<td></td>
<td>27.5</td>
<td>27.51</td>
<td>27.52</td>
<td>27.51</td>
<td>27.51</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Patient’s Right

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td></td>
<td>52.73</td>
<td>52.52</td>
<td>52.63</td>
<td>52.8</td>
<td>52.67</td>
<td>0.12</td>
</tr>
<tr>
<td>Back - Molar</td>
<td></td>
<td>22.46</td>
<td>22.31</td>
<td>22.52</td>
<td>22.32</td>
<td>22.40</td>
<td>0.10</td>
</tr>
<tr>
<td>Base - Molar</td>
<td></td>
<td>27.54</td>
<td>27.53</td>
<td>27.52</td>
<td>27.51</td>
<td>27.53</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Across arch 43.53 43.4 43.61 43.31 43.46 0.13

Table 4.3.3 Lower study model for touch probe scanner

Patient’s Left

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td></td>
<td>48.13</td>
<td>48.29</td>
<td>48.29</td>
<td>48.16</td>
<td>48.22</td>
<td>0.08</td>
</tr>
<tr>
<td>Back - Molar</td>
<td></td>
<td>24.60</td>
<td>24.64</td>
<td>24.59</td>
<td>24.72</td>
<td>24.64</td>
<td>0.06</td>
</tr>
<tr>
<td>Base - Molar</td>
<td></td>
<td>24.36</td>
<td>24.37</td>
<td>24.37</td>
<td>24.36</td>
<td>24.37</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Patient’s Right

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back - Incisor</td>
<td></td>
<td>48.12</td>
<td>48.11</td>
<td>48.20</td>
<td>48.20</td>
<td>48.16</td>
<td>0.05</td>
</tr>
<tr>
<td>Back - Molar</td>
<td></td>
<td>24.24</td>
<td>24.29</td>
<td>24.3</td>
<td>24.26</td>
<td>24.27</td>
<td>0.03</td>
</tr>
<tr>
<td>Base - Molar</td>
<td></td>
<td>24.56</td>
<td>24.57</td>
<td>24.53</td>
<td>24.56</td>
<td>24.56</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Across arch 41.19 41.36 41.25 41.42 41.31 0.10
Francis Alimohamed

**Statistical analysis**

**The Co-efficient variation ratio**

**Within landmarks**

The majority of the time, the C.V. achieved for this method was higher than that of the manual method. However, there was one occasion where a C.V. lower than the C.V. for the manual method was achieved. This was observed on the lower left base-molar landmark measurement (appendix i). A C.V. identical to that of the manual measurement was achieved a further two times on the upper left base-molar and lower right base-molar landmarks (appendix i).

The average C.V. for the upper sets of measurements was higher than that of the lower sets of measurements (appendix i), however both averages were considerably higher than that of the manual method. This observation can be explained by the fact that on five occasions this method achieved the highest C.V. compared to the remaining three methods (appendix i). Overall, the highest C.V. gained was 0.46 for the upper right back-molar landmark whilst the lowest C.V. gained was 0.02 lower left base - molar landmark (appendix i).

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Upper Patients’ left</th>
<th>Upper Patients’ right</th>
<th>Lower Patients’ left</th>
<th>Lower Patients’ right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-incisor</td>
<td>0.10</td>
<td>0.23</td>
<td>0.18</td>
<td>0.10</td>
</tr>
<tr>
<td>Back-molar</td>
<td>0.42</td>
<td>0.46</td>
<td>0.24</td>
<td>0.11</td>
</tr>
<tr>
<td>Base-molar</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>Across arch</td>
<td>0.31</td>
<td></td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.23</td>
<td></td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.3.4 C.V. Values for within landmarks for touch probe scanner*
Across landmarks

Comparing the results of the C.V. test for mean measurements shows that the variation for both the touch probe and the manual method are similar. A similar standard deviation result between the two methods also illustrates this (appendix ii).

Student t Test

Approximately half of the measurements from the touch probe scan are higher than the manual measurements, with the remaining half being lower. There was therefore no consistent directional trend away from the manual measurements and this difference was shown not to be significant (t=0.387, df 13, p>0.05) (appendix iii).
4.4 Laser Scanner

Scanned Data Quality

Figure 4.4.1 Laser - Upper Cast

Figure 4.4.2 Laser - Lower Cast

Percentage of data coverage

Upper surface

\[
\frac{11504 \text{ mm}^2}{12741 \text{ mm}^2} \times 100 = 90\%
\]

Lower surface

\[
\frac{10499 \text{ mm}^2}{12338 \text{ mm}^2} \times 100 = 85\%
\]

The value of 90% coverage for the upper and 85% coverage for the lower does not correspond with the illustrations in figure 4.4.1 and 4.4.2. The illustrations clearly show large areas where data are missing. However, the pieces of ‘Blu Tak’ used to aid the scanning process (chapter 3.6) are also evident in the scanned surface, which increases the surface area of each scan.
Surface condition

The condition of the anatomical surfaces present in this data is good. The surfaces are smooth with only minimal signs of pitting on the horizontal surfaces of both sets of first premolars. There are some signs of noise around the occlusal edges of both models. Again, this has generated a fuzzy surface effect around these areas.

Topology

The percentage of data coverage shows that the overall topology of these surfaces is poor. Whilst the basic structure of both models is present, vital areas of data are missing. Figures 4.4.1 and 4.4.2 clearly illustrate that data is missing from the tips of both the upper central incisors and most of both the lower central incisors almost many other areas. Minimal data on the incisors means that two of the landmarks on each model are incomplete.

Where data are present, the detail reproduced is to an acceptable standard with some signs of overly smoothed areas. However, the use of ‘Blu Tak’ as explained in the Method chapter is evident on the base of both models.

Time Scale

Approximately 10 minutes was required for the preparation period where the position of the scanner was calibrated and ‘Blu Tak’ was attached to sides of the base. The data acquisition period was carried out in two stages which took approximately five minutes overall. Next the data is registered, merged and simplified which can take up
Francis Alimohamed

to 38 minutes. Obtaining an STL file required approximately 0.17 minutes (10 Seconds).

<table>
<thead>
<tr>
<th>Process</th>
<th>Time taken (Mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preparation period</td>
<td>10</td>
</tr>
<tr>
<td>Data acquisition</td>
<td>5</td>
</tr>
<tr>
<td>Obtaining a point cloud</td>
<td>38</td>
</tr>
<tr>
<td>Exporting to an STL format</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td>53.17</td>
</tr>
</tbody>
</table>

Table 4.4.1 Time taken for each process of the laser scans

**Measurements**

All 28 measurements were achieved on both the upper and lower study models. No anomalies were present in the data, although the Across Arch Landmark measurements of the lower study model produced a high standard deviation of 0.81 mm in comparison to the reset of the results in this method.

Of the remaining sets of data, there were two more instances where the deviations in the sets of results were high. The higher of the two can be observed on the patient’s right Back-molar landmark of the upper model, where the measurements varied from 52.02 mm to 52.97 mm giving a standard deviation of 0.23 mm. The second of the two cases can be seen on the patient’s right Back-molar landmark, where the four measurements deviated by 0.20 mm.

The remaining sets of measurements varied between 0.02 mm in deviation to 0.17 mm with the average standard deviation for all the sets of measurements being 0.13 mm.
<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td>53.02</td>
<td>53.11</td>
<td>0.06</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>22.94</td>
<td>22.96</td>
<td>0.04</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>26.43</td>
<td>26.37</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Patient’s Right**

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td>53.27</td>
<td>53.02</td>
<td>0.23</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>22.8</td>
<td>22.82</td>
<td>0.04</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>26.9</td>
<td>26.90</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Across arch**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.35</td>
<td>41.59</td>
<td>0.17</td>
</tr>
</tbody>
</table>

**Table 4.4.3 Lower study model laser scanner**

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td>48.6</td>
<td>48.60</td>
<td>0.02</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>24.94</td>
<td>24.91</td>
<td>0.06</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>22.18</td>
<td>22.22</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Patient’s Right**

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back - Incisor</td>
<td>48.58</td>
<td>48.61</td>
<td>0.03</td>
</tr>
<tr>
<td>Back - Molar</td>
<td>24.51</td>
<td>24.55</td>
<td>0.20</td>
</tr>
<tr>
<td>Base - Molar</td>
<td>22.26</td>
<td>22.28</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Across arch**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Ave</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>39.13</td>
<td>40.33</td>
<td>0.81</td>
</tr>
</tbody>
</table>
**Statistical analysis**

**The Co-efficient variation ratio**

**Within landmarks**

The general trend observed for this method was that all of the C.V. results were higher than that of the manual method. On nine measurements this method achieved the highest C.V. value compared to the remaining three methods (appendix i) This led to the joint highest overall average C.V. of 0.23 for the upper landmarks.

The overall average C.V for the lower landmarks was a great deal higher then that of the manual method (appendix i), however this was mainly due to a high C.V. in comparison to the remaining three methods, achieved by the lower Across Arch Landmark (appendix i). Overall the highest gained was by the across arch landmark. It is worth noting that this is also the highest C.V. achieved out of all the sets of measurements. The lowest C.V gained was by the lower left back-incisor landmark (appendix i).

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Upper Patients' left</th>
<th>Upper Patients’ right</th>
<th>Lower Patients’ left</th>
<th>Lower Patients’ right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-incisor</td>
<td>0.11</td>
<td>0.44</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Back-molar</td>
<td>0.19</td>
<td>0.19</td>
<td>0.24</td>
<td>0.81</td>
</tr>
<tr>
<td>Base-molar</td>
<td>0.19</td>
<td>0.08</td>
<td>0.17</td>
<td>0.13</td>
</tr>
<tr>
<td>Across arch</td>
<td>0.40</td>
<td></td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.23</td>
<td></td>
<td>0.49</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.4.4 C.V. Values for within landmarks*

**Across landmarks**

The C.V. and standard deviation values for the laser scanner are higher than that of the manual measurement. This suggests a greater amount of variation is present in
measurements obtained from the laser scanner data and this observation is backed up by the result of the Student t Test below.

**Student t Test**

A comparison of the two overall means for this method and the manual measurements shows the greatest difference of the three comparative techniques (appendix ii). However, this difference turned out not to be significant ($t=1.683$ df 13, $p>0.05$) (appendix iii). An examination of the measurements shows that some of the mean measurements of the laser scanner are higher and some being lower then the manual measurements, and therefore a consistent pattern cannot be identified.
Summary of C.V. results

Within landmarks

The co-efficient variance ratio was first used to compare the variability present in the repeated measurements for each landmark across each method.

Overall the majority of the C.V obtained from the manual measurements for each of the sets of measurements set the benchmark and was the lowest obtained for each landmark across the methods.

In comparison, the C.V. obtained from the structured light measurements showed that there were several times where the C.V for these two methods were the same whilst the overall higher average C.V. was accounted for by five results which were considerably higher then that of the manual method.

The majority of the C.V. results obtained from the touch probe measurements were higher than that of the manual measurements; however on one occasion a lower C.V. value was achieved.

The trend observed from the C.V. values of the laser method was that they were mostly a great deal higher than that of the manual method which was evident by the joint highest average C.V value.

Across landmarks

The co-efficient variance ratio was then used to compare the variability across the mean measurements for each method. The results from the C.V. test revealed that the
mean measurements for the structured light scanner varied less than that of the manual method whilst the mean measurements for the touch probe scanner had a similar amount of variation to that of the manual method. Finally the C.V. values for the laser scanner are higher than the C.V. values of the manual measurement.

It is worth noting that all of the C.V. values obtained are well below 1% and although an average variation of eight times more than that of the most consistent method seems high, in reality this is not the case. It was then used to compare the variability across the mean measurements for each method.
4.5 Scoring index

The scoring index devised takes into account the factors which are being addressed in this investigation not only allows each system to be compared by each factor but also enables the overall feasibility of all the systems on test.

Each scanning system was given a rating between 1 and 5 for each of the factors in the table below, where 5 is ideal and 1 is poor. Bonus ratings can be achieved for accuracy and time. The rating awarded was based on the criterion devised for each factor (See chapter 3.8).

<table>
<thead>
<tr>
<th>Scanner Factor</th>
<th>Structured light</th>
<th>Touch Probe</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Accuracy</td>
<td>5</td>
<td>4.5</td>
<td>3</td>
</tr>
<tr>
<td>Scanned data quality</td>
<td>4.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Time Operator time</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Overall time</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Space</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>20.5</td>
<td>21.5</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.5.1 Results from scoring index.

Ease of use

From the ratings, the touch probe scanner was the easiest to master, closely followed by the structured light scanner and the laser scanner.

Accuracy

The rating for this factor was awarded for the number of mean measurements that were $\pm 0.5$ mm the values achieved by the manual method.

The structured light scanner scored a top rating as there was $\pm 0.5$ mm difference between the average measurements achieved by the manual method compared to that of the structured light method for all 14 landmarks.
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The touch probe scanner closely followed with a rating of 4.5 as there was \( < \pm 0.5 \text{ mm} \) difference between the average measurements achieved by the manual method compared to that of the structured light method for 12 out of the 14 landmarks. The Laser scanner scored the lowest rating. Only half of the 14 measurements were within \( \pm 0.5 \text{ mm} \) of the average manual measurement.

**Scanned data quality**

The touch probe and laser scanners achieved similar scores in this category near the bottom of the ratings whilst the structured light scanner achieved the highest score near the top of the ratings.

**Time**

This factor is divided into two categories. The first category assesses the scanners on the amount of operator time required to generate a three-dimensional surface of one study model. The second category focuses on the time taken for the whole scanning process required to obtain a scan and generate a three-dimensional surface of one study model.

The touch probe scored the highest rating for the operator time category as the presence of an operator was only required for the initial setup. This was followed by the laser scanner and then the structured light scanner as both of these methods required supervision throughout the whole process.

The laser scanner scored the highest in the overall scan time category as it was the fastest scanner to obtain a scan and generate a three-dimensional image of one study model, taking under 60 minutes. This was followed by the structured light scanner,
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which took 135 minutes. The Touch probe scan required the longest time to meet this criterion of over 600 minutes.

Space

The touch probe method gained the highest score in this factor, as the scanner itself required little more space than a normal pc and its accessories. Both the structured light and laser scanners ideally required a dedicated room to perform a successful scan.

Summary

The touch probe scanner achieved the highest overall rating which was closely followed the structured light scanner. The laser scanner achieved the lowest rating by a fair margin. The touch probe scanner came top in three times out of the six categories. The structured light scanner came top in two categories whilst the laser scanner came top in only one category.
4.6 Summary

This chapter detailed the results obtained firstly from the physical measurements of the master study models and then from each of the three different scanning techniques. General trends such as the biggest variation between the four results for each measurement were commented upon and the average standard deviation for each method was noted. As expected, the manual measurements varied the least whilst the measurements taken from the laser scan varied the most.

Next, the anatomy of the surfaces produced from each scanning method was assessed by looking at the percentage of data coverage, the surface condition and the topology of the surface. It was found that the structured light scanner produced the best over all surface and was the only one that could be used for complete cast analysis.

Statistical tests were carried out on all of the data obtained from each scanner. The coefficient variance ratio was first used to compare the variability present in the repeated measurements for each landmark across each method. It was found that all of the methods achieved a higher average C.V. than that of the manual method.

It was then used to compare the variability across the mean measurements for each method in which the measurements from the touch probe scanners data showed a similar amount of variation to that of the manual method. The final statistical test was the student’s t test, which was used to determine whether the variations in the results between each scanning method and the manual method occurred by chance, or whether it was due to the method itself. The results from this test revealed that the difference in the measurements from the structured light scanner compared to the
manual method was significant whilst the differences observed by both the touch probe and laser scanner compared to the manual method were not significant.

Finally using the data gathered from this section, each system given a rating out of 5 where 5 is ideal and 1 was poor for factors which were being looked at in this investigation. The touch probe scanner achieved the highest overall rating.

The next chapter will discuss the findings of these results comparing each scanning method with the results gained from the physical measurements.
5. Discussion

This chapter will discuss the findings of the results from this investigation, firstly by analysing the quality of the scan data, then relating the concepts of reliability, validity, accuracy and feasibility to each factor considered. From these findings the best overall scanner will be revealed. The limitations of this investigation will be discussed and the method used will be evaluated. Finally, further research into the use of three-dimensional scanners for the storage of dental study models will be suggested.

5.1 Scanned data quality

The quality of the data produced by each scanner was assessed by looking at the percentage of data coverage, surface condition and finally the topology of the surfaces each method produced.

Magics, the software used to obtain measurements on the scanned, surfaces revealed that the data produced by the structured light scan contained no 'bad edges'. This means that there were no gaps in the surface and as a result, it was judged to have 100% data coverage. Therefore, the surface area calculated from this data set was used as a benchmark to calculate the percentage of data coverage of the surfaces produced by the remaining scanning systems. The nature of the structured light scanning system meant that this result was as expected. Although individual surfaces of each study model had to be scanned separately and pieced together to form a complete surface, the data gained from each scan was aligned directly to the previous collection of scans after it had been acquired. This allowed the progress of the data acquisition to be constantly monitored, which enabled holes in the data to be identified and scanned before moving on to the next model.
Of the two remaining systems, the laser scanner produced the higher percentage of data coverage for both the upper and lower study models. However, figures 4.4.1 and 4.4.2 show that these could be anomalous results due to the large areas of missing data in the palatal regions of the upper and lingual regions of the lower. The method used during the laser scan detailed in section 3.6 noted that problems were found whilst piecing 6 individual scans together because the software was unable to identify sufficient landmarks along the straight edges of the bases. To solve this issue ‘Blu tack’ was added to the bases to form artificial landmarks that were recognised by the software. The addition of the ‘Blu tack’ increased the overall surface areas of each study model and it is clear from figures 4.4.1 and 4.4.2 that these artificial landmarks have been included in the scanned surfaces. As a result, this increased the percentage data coverage giving higher than normal values, which do not give an accurate representation of the surfaces produced. The gaps in the data are due to the method used during the scanning process. Unlike the structured light method, the laser procedure acquired six consecutive scans at fixed points of 60° intervals before the scans were merged together. As a result, any area of the cast not within the scanner’s line of sight in any of the six positions would not be captured.

Figures 4.3.1 and 4.3.2 show screen shots of both surfaces produced by the touch probe scanner. As there are no obvious holes in the data, the percentage of data coverage is expected be a similar value to that of the structured light scan. However, a closer inspection of these surfaces reveals that the buccal and labial surfaces of the upper anatomy and the labial and palatal surfaces of the lower anatomy suffer from severely jagged surfaces, which indicate where data has been lost. In most of the aforementioned areas, the jagged surfaces run from the occlusal tips of the teeth all
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def the way down in a vertical manner into the sulcus and as a result, details such as the bulbous regions of the teeth and the gingival margins have not been reproduced. This jagged surface is also evident around the sides of the base of both models and is another area where data has been lost.

The condition of the surfaces produced by the structured light scan was generally in good order, with only a small amount of noise around the dentition. The nature of the structured light scan meant that any dust particles in the air around the study model would be picked up by the scanner and its presence on the final surface is known as ‘noise’. However, the majority of noise was removed using the Alias-Wavefront Spider software during the polygonising process (chapter 3.6).

Where data was present, the laser scanner produced a good surface, again with small signs of noise around the occlusal edges. Noise was present in this scan for the same reason as the structured light system and was kept to a minimum by using the RapidForm 2004 software (chapter 3.6).

The touch probe scanner produced the worst surface out of the three scanning systems with the severe jagged edges around the buccal and labial surfaces of the upper and the labial and palatal surfaces of the lower. The only advantage was that there was no noise present on either of the surfaces. However, this was as expected as dust in the air would not be picked up by the probe.

The data obtained from the structured light scanner offered the best topology, providing a good reproduction of the anatomy and all landmarks of both study
models. This provides evidence that after the landmarks had been revised the structured light system produced no further issues in obtaining the required data to reproduce them to an acceptable degree. Only the slightly rounded off edges and corners of some landmarks lowered the quality of the overall surface, which was due to the nature of the structured light scanner. During the scanning process, points are thrown all over the study model being scanned in a random fashion and as a result, there are no set points to clearly define any edges. Therefore, during the polygonising stage in Alias-Wavefront Spider, the surfaces are created by joining up the points in the most direct way possible, which results in rounded edges.

Due to the jagged surfaces of the study models, the data generated by the touch-probe system produced a poor representation of both study models. This appears to be the result of using the wrong type of stylus. This affected the areas around the landmarks, which have been rounded off.

The topology of the surfaces produced by the laser scanner was poor, which was mainly due to the large gaps in the data of both study models. These gaps are also evident around some landmark surfaces, which will have an effect on the measurements obtained from these landmarks. Where data is present, the topology is acceptable.

The quality of the scanned data is an important factor when assessing the validity of a system. We should be able to have confidence that our measuring device is measuring what it is supposed to measure (Coolican, 2004). It is obvious that both the touch probe and laser systems do not relate to this definition of validity as they are missing
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data in areas and have additional data in others. As a result, the surfaces generated by these scanners cannot replace the physical study models as they do not provide a precise three-dimensional time-related record (Ayoub et al, 1997) and do not include all erupted teeth, the palate and the full sulcus depth of the patient (Mitchell, 1996). The structured light scanner was the only system to produce surfaces that stand up to close scrutiny.
5.2 Time

The time taken to achieve a scan of a single study model was recorded, as time is an important factor to consider when judging the feasibility of each scanning system. A dentist treats roughly 20 to 40 patients a day (Gray, 2005) and whilst study models are not required for all of these patients it is likely that study models will be required for some. Taking this into account, if a three-dimensional scanning system was used as an alternative to the conventional means of study model storage then in order for it to be feasible, it must be able to keep up with the number of study models required during a typical working day.

This factor was split into two categories. The first category considers the scanners on the amount of operator time required to generate a three-dimensional surface of one study model, whilst the second category focuses on the time taken for the whole scanning process required to obtain a scan and generate a three-dimensional surface of one study model.

The results from the first category reveal that the touch probe scanner required the least operator supervision out of all of the techniques, which was largely due to the fact that once the machine was setup with the cast in position, the remainder of the process was fully automated. This can be seen as a great advantage as during this time the operator can carry out other tasks or the scanning can be left to proceed over night. In contrast, the remaining two methods required full supervision throughout the entire process and as a result achieved a lower rating. However, the laser scanner was awarded a higher rating than the structured light scanner in this category because the
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time taken for the overall process was quicker and therefore less operator time was required.

The second category showed that of the techniques investigated here, the laser scanner was the fastest system to produce a three-dimensional surface and the only system in this study to achieve this in less than 60 minutes (1 hour). The structured light scanner was the next fastest and took 135 minutes (2 hours 15 minutes) to produce a three-dimensional surface. For both of these systems most of the time was taken obtaining the point cloud data. It is therefore possible that as the operator becomes more experienced with working with dental casts the time required for this process could be reduced.

The touch probe scanner took by far the longest time to achieve a surface requiring 664 minutes (11 hours 4 minutes). The majority of this time was accounted for by the data acquisition stage. However, after the initial preparation period, the remaining processes were automated, which can be seen as a bonus as the scanning process can be left over night or the operator can carry out other tasks during the day.

It is worth noting that as the time given was only for one study model, the value needs to be doubled to calculate the overall time required to scan a set of study models. Therefore, the quickest time that a full set of models can be scanned is approximately 106 minutes (1 hour 46 minutes) by the laser scanner. As this system requires an operator for the whole process, this represents a considerable amount of time compared to the working day time. However, such a system may be feasible in an environment where a low number of study models are used.
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The structured light scanner would require around 270 minutes (4 hours 30 minutes) and like the laser scanner required a full time operator. In reality, this system is simply not fast enough to cope with the number of study models required in a typical dental environment.

Although both of these systems can not be recommend for scenarios where there is a high volume of dental study models, unlike the touch probe system, both systems use points to capture the surfaces of the object being scanned. As a result, there is a possibility that the overall time could be reduced by not converting the point clouds in to STL files. This is more relevant to the structured light scanner, whose overall time would be reduced to 105 minutes then the laser scanner as achieving an STL file from the data produced from this system only took just over 10 seconds. This is an extremely feasible option due to the fact that the vast majority of the data stored will never be used. However, whilst this helps to reduce the process time, it would not be possible use this type of raw data for research, which would be a disadvantage of such a system.

The touch probe scanner would require approximately 1228 minutes (22 hours 8 minutes). Whilst the majority of this time the process is fully automated, the fact that it can only scan one set in 20 hours out weighs this advantage and as a result, it is fair to conclude that in terms of time this system cannot be feasibly used for the storage of study models.
5.3 Statistical analysis

The results obtained from the manual measurements were taken to be the benchmark to which all of the measurements from the scanned data would be compared. This was because at this time the only reliable method of obtaining measurements from a dental cast would be via the manual method. The comparison of the measurements obtained from the scanned data to that of the manual measurements will give an idea of which scanner produced measurements which were not only the closest to the current method but which also showed similar variance.

Two statistical tests were applied to the results obtained from this investigation. The co-efficient variance ratio was used firstly to compare the variation of the measurements obtained within each of the landmarks of each scanner and secondly to compare the variation across the mean measurements for each method. The student t test was run to determine whether the differences between the mean measurements obtained from the manual measurements and that of the scanned data occurred from the method or by chance.

The co-efficient variance ratio (C.V.) of the measurements within landmarks illustrates the amount of variation present within the four repeated measurements taken for each landmark for all methods. According to Carmines et al (1979), reliability can be tested to see whether a process yields the same results on repeated trials. Therefore, the closer the repeated results are to one another, the lower the C.V., the more reliable the system is.
With the lowest average C.V. of 0.03 for both the upper and lower study models it would be fair to conclude that the manual measurements were the most reliable out of the four systems tested. This also demonstrates that reliable measurements can be obtained from the devised landmarks (Section 3.4). However, higher than average C.V. values were obtained for the upper right back-molar and lower right base-molar measurements, which indicate that slight inaccuracies were present along the planes of these landmarks. This was as expected due to the fact that the measurements were being taken directly from the model rather than from a scan of the model where data can be lost in the process.

Of the scanning systems, the data obtained from the structured light scanner produced the lowest amount of variation for both the upper and lower study models with average C.V. values of 0.10 for the upper and 0.12 for the lower. Both these C.V. values were affected by three high C.V. values on the upper (left and right back-molar and across arch landmarks) and two high C.V. values on the lower (right back-molar and across arch landmarks). Out of these five values, the high value for the upper right back-molar C.V. could be expected as this measurement also had a higher than normal C.V. on the manual measurement. However this scanned C.V. value is still higher than that obtained from the manual measurements. The remaining four high values could be due to error in the method. Over three landmarks, the measurements obtained from the structured light scanner data showed the same amount of variance as the manual measurement, equalling the reliability in these areas. A lower C.V. than the manual method was achieved four times out of the 14 measurements, (on the upper right base- molar landmarks and the lower left back- incisor lower right back-incisor and finally the lower right base-molar landmarks).
Over these landmarks, it can be said that the measurements from the structured light scanner are more reliable than that of the manual measurements. Indeed when comparing the C.V. values for the mean measurements across the landmarks for the manual and structured light method, the structure light measurements achieved a slightly lower value. As a result, it can be concluded that there is less variability across the mean measurements from the structured light data.

Out of the two remaining systems, the measurements from the touch probe scanner data showed the least variation. Whilst an average C.V. for the upper measurements was identical to that of the laser measurements, the measurements obtained from the touch probe scanner showed variations that were closer to that of the measurements from the manual method. Less variation than the measurements from the manual method were seen over the lower left base-molar landmark making these data more reliable over this area whilst the data were as reliable over the upper left base-molar and lower right base molar regions. Significantly more variation than the manual measurements was observed over three out of the four back-molar landmarks, which points to problems in the scanned data on the landmarks involved in these measurements. As with the across arch measurements from the structured light data, both across arch C.V. values were considerably higher than those achieved by the manual method. The C.V. values obtained from the mean measurements across the measurements landmarks show that this method produced measurements that varied slightly more than the manual measurements.

The measurements taken from the data produced by laser scanner showed the most variation. Only the lower back-incisor measurement achieved C.V values that were
close to that of the manual method. The remaining C.V. values were considerably higher than that of the manual method showing that the laser system had problems with gathering enough data to correctly replicate most of the landmarks on the screen. The C.V. values obtained from the mean measurements across the landmarks show that this method produced measurements that varied more than the manual measurements.

It is worth noting that for all scanning methods the highest C.V. value gained was for the across arch measurements which illustrates that this landmark was not suited to the scanning systems.

In summary, the results from the C.V. test shows that the manual measurements produced the most reliable results, whilst of the scanning systems, measurements taken from the structured light scanner were the most reliable and measurements taken from the laser scanner were the least.

The student t test was used to determine whether a real difference existed between the means within landmarks obtained with the manual measurements compared with those obtained by each of the scanning systems. This analysis used measurements taken across landmarks and a p value of <0.05 was taken to be significant.

The structure light method produced mean measurements that were generally slightly higher than the mean manual measurements. The p value obtained from the t test indicated that this difference has occurred because the scanning method gives significantly higher readings then the manual method.
The touch probe method produced an uneven mixture of mean measurements with some being higher than that of the manual measurements whilst the others were lower and therefore a consistent pattern cannot be identified. The t test revealed that the differences between the mean measurements of the two methods were not significant. This shows that although the methods do not differ this is not in a consistent manner.

The result of the t test run on the mean measurements from the laser scanner data revealed that as with the touch probe data a consistent pattern when comparing the mean measurements of the manual method to the laser scanner could not be identified. However the resulting p value revealed that the difference was not significant implying that just like the touch probe scanner, the difference was inconsistent and that neither method produced significantly greater measurements, which is not surprising as the variability in the scanned measurements was evident in the C.V. values. Most of the variation occurred in the measurements made from this scanning method.

The t test revealed that the mean measurements of each landmark taken from the structured light scanner data were the only set of measurements that were significantly different to that of the manual measurements. However, it was also the only set of measurements that varied consistently in one direction of the manual measurements. The t test indicated that both the mean measurements of each landmark taken from the touch probe and laser scanner data were not significantly different to that of the manual measurements. However, this is because a consistent pattern of mean measurements could not be identified in relation to the mean manual measurements, with some higher and some lower than that of the manual measurements. As a result, both methods resulted in overall mean values that were closer to the overall mean
value of the manual method than the structured light scanner, which is why the t test returned a non-significant result.

Although the differences between the mean measurements of each landmark from the structured light data were significantly different to the mean manual measurements, as the differences were always consistently slightly higher than the mean manual measurements, this system would produce reliable results. As both the mean measurements of each landmark taken from touch probe and laser scanner data were inconsistent, it would be difficult to determine the reliability of the data gathered by these two systems.

Reliability is that factor being addressed by considering the results from these statistical tests. Manual measurements aside, the measurements that clearly produced the least variance were from the data produced by the structured light scanner and as a result, this was the most reliable system on test.

The measurements from the laser scanner data varied the most within the landmarks and lacked consistency across the landmarks. As a result, it was the least reliable system in this group. However, only one C.V. value was over 1% when comparing the variability within the landmarks, which shows that in reality none of the measurements varied by an excessive amount.
5.4 Ease of use

The results from the scoring index revealed that the touch probe scanner was the easiest scanning method to operate. The system is accompanied with a good set of help files and the offer of a three-day training course to all customers. The touch probe system was also the only system which could be left unmanned after the initial setup of the model and the input of x y and z planes thus eliminating the complex processes of manual polygonising and merging of data.

Both the structured light scanner and the laser scanner achieved the same rating. Full supervision was required for both systems from the initial set up to obtaining a final surface in an STL file format. The operator of the structured light system commented that the task was not a difficult one and was simply a case of following a list of procedures. With experience, the process becomes easier as the operator will get better at deciding the angles from which to scan in order to gain complete data sets in an efficient manner. The difficult parts of the structured light scanning process were the processes which followed the initial scan as it takes longer to learn how to process the data (the removal of ‘noise’) and use the software to create polygon data from the scan data.

Ease of use is an important factor when considering the feasibility of a system. If a system is difficult to operate then its feasibility will be low as a large amount of time will be required to train the potential operator(s) to ensure that an accurate scan is obtained.
The limitation of this study was that different operators were used to undertake the scans with each system. Due to time restrictions, it was not feasible to train one person to operate each system and as a result, experts in each method were used to obtain the scanned surfaces.
5.5 Accuracy

Accuracy was a factor which was included in the scoring index and looked at how close the average measurement for each landmark for all three scanning system came to those obtained by the manual measurements.

Daily and Bourke, (2000) defined accuracy as a measurement which is precise and unbiased. In the case of this study, none of the systems can be deemed as 100% accurate as out of the 42 average measurements (14 from each system) only one was identical to the corresponding manual measurement. However Daily and Bourke also stated that a system which does not provide 100% accuracy may still be judged to be accurate for the purposes at hand. For the purpose of study models a 100% level of accuracy cannot be expected as studies by Parfitt (1960), Millstein (1992) and Cohen et al (1995) amongst others, revealed that factors such as tooth mobility, die stone stability and impression material accuracy needed to be taken into account. As a result an accuracy of $<\pm0.5$ mm was considered to be acceptable, agreeing with the findings of Bell et al (2003).

The structured light scanner achieved the highest rating and was the only system in which all 14 mean measurements were $<\pm0.5$ mm that of the manual method and due to this it can be said that this is a more consistent method as the differences between all of mean landmark measurements compared to the manual method were not significant. As a result, this system can be deemed the most accurate in this study.

The touch probe scanner achieved the second highest rating for accuracy using these criteria, not achieving a top rating as two of the measurements fell outside the $<\pm0.5$ mm criteria.
The laser scanner scored the lowest rating for this factor and as a result, it is fair to state that this system was the least accurate of the three scanning methods in this study. Only half of the average measurements were well within the $< \pm 0.5$ mm criteria.

The criteria used to determine the accuracy of each system did not take into account the fact that the touch probe scanner achieved the closest mean measurement to the manual method seven times and in addition to this on one occasion achieved the same mean measurement. In comparison, the structured light scanner achieved the closest mean measurement to the manual method just six times. The initial criteria accommodated these findings by offering bonus ratings for each time the mean measurement was the closest to that of the manual method and as a result the touch probe scanner gained the higher ranking (appendix v). However, generating scanned surfaces that fell within an acceptable tolerance was considered to be of more importance in this investigation and resulted in the removal of the bonus ratings from the criteria.
5.6 Space

Space is a factor of much importance in this investigation, as the storage of study models has become a major problem taking up rooms of valuable space in both hospitals and practices alike. In 2001, the BBC reported that orthodontic treatment had doubled since the 1990's and with the British Dental Associations recommended retention time for dental records of 11 years for adults and up to the age of 25 for children, the resultant storage problem is of no surprise. A study conducted by McGuiness and Stephens (1991) revealed that hospitals need to access up to 200 sets of study models a day, so storage off-site is not a feasible option as a large amount of time will be spent ferrying models to and from this facility (Ayoub et al, 1997). McGuiness and Stephens concluded that an alternative method of storing dental study models was required.

Using three-dimensional scanning to store study models is a potential alternative. The data obtained from the scanning of the study models can be stored on a CD, which is more space efficient than a standard size study model box. However the space that a three-dimensional scanning system takes up needs to be considered as in many cases, the scanning system is comprised of specialist equipment which in turn takes up valuable space. In an environment in which space is an issue, the less space a system requires the more feasible it is.

The touch probe scanner scored the maximum rating for this factor. Only two components were required which consisted of a computer and the scanner itself, which was self contained in one shell making this system relatively compact. As a result it was possible to move the scanner if the space was required. The fact that the scanner did not require a specific location such as a dark room was also a bonus.
Both the structured light and the laser scanners achieved the same low rating. This was because they both required bulky equipment that took up a whole room. Although both sets of equipment could be packed up and moved when required, the amount of equipment involved meant that this would be a lengthy process.
5.7 Cost

Cost was a factor that was initially included in the scoring index. The cost of everyday laboratory equipment was investigated to formulate a criterion for this factor. Current dental laboratory equipment catalogues were reviewed in order to determine cost boundaries to which the cost of the scanning equipment could be compared. For each of the cost boundaries an example of the equipment found within it has been given. The sum of £20,000.00 was taken to be roughly the price of the most expensive piece of laboratory equipment and systems that exceeded this price were awarded the lowest rating of 1. However, other equipment may have been available on the market that exceeded this cost at the time of this study. However, this value was taken to be a good average price of the top laboratory equipment. The total cost of all the equipment required to carry out the three-dimensional scan and produce a surface was taken into account in this assessment. However, rating the scanning systems using the aforementioned criteria resulted in a rating of one for all methods. As each scanner achieved the same low rating, the cost factor had no bearing on the overall total and therefore this criterion was removed from the scoring index.

The total cost of each system is shown in appendix vi and includes the scanner itself and all additional equipment required to carry out a scan to the stage where a surface can be produced, viewed on a screen and saved as an STL file. The prices quoted are an approximation, which was correct at the time of this investigation.

The structured light scanner was the most expensive system tested in this investigation, with the scanner alone amounting to £60,000.00. A price for both pieces of software used in the structured light process were unobtainable largely due to them
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being obsolete at the time of this study and attempts to contact both the manufacturers and the European distributors to obtain the prices of their replacements were unsuccessful. However, the fact that the structured light scanner itself cost significantly more than the complete touch probe and laser systems and that the additional cost of the software packages would only increase the total price meant that the absence the software prices did not affect the final ranking.

The laser method was the second most expensive scanning system and whilst there were more components involved, prices were obtained for all of them. However, the laser scanner used in this investigation, the Minolta Vivid 900, had recently been superseded by a newer model, the Minolta Vivid 910, therefore the total price quoted here is for the 910.

The cheapest system was the touch probe scanner in which the whole system was given as a single price direct from the manufacturer.

The cost effectiveness has a bearing on the feasibility of a scanning system. As all three systems are very expensive, if the feasibility of having one or more systems in a hospital, practice or laboratory was solely judged on cost, it would be very low.
5.8 Overall comparison

The touch probe system achieved the highest final rating in the scoring index. However this does not mean that it was awarded the best mark for each factor. This system was the easiest to operate, the most flexible in terms of space and also performed well in terms of accuracy, but was the worst for time taken and produced a poor scanned surface. Results from the statistical tests revealed that the measurements obtained on the data produced by this method varied more than the manual and that of the structured light method but less than that of the laser system. The student t test concluded that the variation from the manual method meant that the scanning method produced significantly higher readings than the manual method.

Achieving an overall rating which was slightly lower than the touch probe system, the structured light scanner came in second. This method produced the only scanned surfaces which accurately portrayed the physical study models and was also the most accurate as all measurements taken from the data fell within acceptable levels. The statistical analysis showed that the measurements from this method varied the least out of the three scanning systems producing the closest variance to that of the manual method. However, the student t test revealed that the variation from the manual method was due to chance and that although the methods differ; this is not in a consistent manner.

The laser scanner scored the lowest rating overall. This method was the best for time, achieving the quickest scan. However, it produced a poor scanned surface and the measurements taken from this data varied the most, although not in a consistent manner.
5.9 Limitations

This section will discuss factors that were seen as limitations in this investigation.

Time

Time was identified as a limiting factor in this study for a number of reasons. Firstly, it was only possible to produce one set of scanned surfaces for each scanner. If time had permitted the production of more scans for each method, then it would have been possible to determine whether the surfaces produced by the first scan could be improved upon and if this surface was an anomaly. Secondly, it was not possible to investigate the use of the scanned data produced by each of the three methods to reproduce the set of dental study models using computer aided manufacture (rapid prototyping). It would have therefore been possible to establish if the data from each system could reproduce a lifelike physical model. Finally, as the touch-probe scan took place outside of the University of Wales by a commercial company there was a restricted amount of time in which the scanning process could take place. For example, the commercial company’s first attempt produced a surface that was unsatisfactory for this investigation and as a result, the models had to be rescanned. However, due to the commercial company’s busy schedule this second scan ended up taking a long time.

Scanners

Three different methods of three-dimensional scanning were tested in this investigation. However, only one make of scanner for each method was reviewed. It is possible that different makes of the same scanning method could be more suited to the scanning of dental study models and therefore producing better results when those
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generated by their counterparts used in this study. It was also found when gathering information regarding the cost of each scanning system, that some of the equipment and software used in this investigation had now been superseded by newer versions, referring to the software used in the structured light scan and the laser scanner itself. It is fair to assume that revisions have been carried out to both of these components to improve their performance, and as a result, it is possible that they may have produced better results. The inclusion of both this newer laser scanner and structured light software would have given a better comparison of the equipment available at the time of this investigation. However, the availability and access to both of these components prevented their use in this study.

**Software**

It is possible that there are more advanced software packages available which are able to manage the data acquired by scanners more efficiently. As the touch probe scanner had its own built in software, this limitation is only relevant to the structured light and laser scanners, where the majority of their overall process time was taken up by the final two stages - obtaining a point cloud and exporting to an STL format. If different software packages were trialled, possibly fully automated ones, with these scanners when carrying out the final two stages then it is a possibility that both their overall process time and operator time could have been decreased and thus making both these scanners a more feasible option.

**Operator**

As with Bell et al’s study in 2003, the same operator was used to carry out all of the manual measurement processes eliminating the possibility of variation in
measurement due to different operators. However, the scanning processes were
carried out by operators who were experienced in using a specific system and as a
result three different operators were used during the scanning processes. This brings
about the element that one operator could be more experienced in using their
particular scanning system than another operator is at using theirs. This is more
relevant to the structured light and laser method as opposed to the touch probe system
as after the initial setup the touch probe scan is fully automated. However, both the
other methods require the merging and polygonising of data to be carried out, which
is a skill that improves with experience. Training a single operator to carry out scans
using all three systems would have eliminated this problem. However this was not
feasible due to time constraints.

Scoring Index
The scoring index devised in this investigation to aid the comparison of each scanning
method is very basic and based on criteria that were designed to give a quick
overview of each system. Due the fact that the main aim of this study was not to
solely develop a scoring index, a more detailed index was not formulated. As a result,
it is fair to state that the scoring index uses very limited criteria to judge each factor.
The main limitation of this index is the fact that it does not take into account that
different factors may be more important than each other and as a result it was
assumed that each of the factors were as important as each other. For example, if time
and accuracy are seen to be more important than space and ease of use, then this level
of importance should be reflected in a higher rating which will result in a more
realistic comparison being made.
5.10 Evaluation of method

There were many elements of the method used in this investigation that had not been applied to any previous study in this field. The landmarks devised were different in the fact that they were not only developed from a dental point of view but also from engineering. This can be seen as a definite advantage not only over previous investigations in this field such as Ayoub et al (1997) Bell et al (2000) but also over other measurement systems used in dentistry research by Singh and Savara (1964) where the general trend was to use specific points or lettering on the dental study model as landmarks. Unlike the method employed by these authors the measurement planes used in this investigation were not only successful in providing a permanent landmark which did not alter throughout the study but also eliminated all of the accuracy problems, detailed in section 2.6, involved when taking measurements from a single point. The devised landmarks were also successful in the fact that on the whole they were recognised by all three scanning systems after the modification to the original design was carried out (section 3.6). This was not to say that all of the scanning systems were able to produce scanned surfaces on the computer screen that perfectly captured all of the landmarks. It was identified that all of the scanners had problems scanning the molar landmark around the edges that were at 90°. As these landmarks were used when taking the across arch measurement it is likely that this is the reason why the across arch measurements taken from the data produced by all of the scanners varied a great deal more than the manual measurements taken across this landmark.

Perhaps the biggest problem with using such landmarks was creating each plane. In order to produce such accurate planes an engineer's Universal Milling Machine was
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employed. As this machine is usually use to mill metal and not dental die stone it was
difficult to prevent the milling drill piece from chipping away bits of the surrounding
die stone and although a change in the initial technique kept this to a minimum, it was
not possible to prevent this from occurring.

Only one set of dental study models was used throughout this investigation, which,
ensured that each scanner had the exact same objects to capture. However, this proved
a problem when the models were sent away for the second time to the commercial
company who carried out the touch probe scan. The second scan took a long time to
be completed and as a result the company were in possession of the models for this
whole period which meant that no further scanning could take place during this time.
If duplicate models were taken, then this delay would have not occurred.

The Scoring index developed was another first as research showed that such a system
had not been used in previous investigations. It enabled an immediate comparison of
each scanning system to be made in terms of the identified factors and in terms of
reliability, validity, accuracy and feasibility. However, as acknowledged in section
5.9, it was based on a basic and limited index. While it was felt that the criteria
developed to score the factor of accuracy was adequate due to past research, in order
for the scoring index to be more accurately applied to judging scanning systems in the
future, certain criteria will need to be revised.

The ease of use was the first factor to be judged in the scoring index, which took into
account the amount of training and computer skills required. However no specific
values were given. Stating the number of hours required to become competent at fully
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operating the scanning system and the level of computer skill required would enable a scanning system to be scored more accurately, as would rating these areas separately at first, then combining them to achieve an overall rating.

The scanned data quality was judged by assessing three main areas; percentage of data coverage, scanned data quality and topology. The current criteria combined each of these three areas, which in some cases made it hard to accurately award a rating for the scanning system. Developing separate criteria for each of these areas and adding up the ratings to give an overall rating for the quality of the data would make this factor easier to judge. This would also allow a comparison to be made between the percentage of data coverage, scanned data quality and topology for each scan, increasing the versatility of the scoring index.

The criteria generated for the space taken by a system would also benefit from a revision. The present criteria compared the space taken by the scanning system equipment to the space taken by a PC and accessories and whether or not the system can be moved with ease, which only gives a vague idea of the space involved. This could be improved by specifying the floor space required all of the scanning equipment in metres squared (m²), as this would generate a more accurate indication of the space required for each system. A separate criterion could then be added assessing portability of the equipment involved with the rating achieved being added the main rating for this factor. Separating this category would make it easier to judge a system more accurately.
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It was possible to gain a half rating in this scoring index if the result of the scanning method for that factor fell in between the specified criteria. However, this meant that an exact criterion was not given for such a result. If the number of ratings were increased from 5 to 10, then it would be possible to have 10 justified ratings on which to judge the system for each factor, allowing for only whole number ratings to be achieved.

One of the biggest limitations of the scoring index is that it does not take into account the fact that one of the identified factors maybe more important then another, as each factor (with the exception of time) was awarded an equal weight in the ratings. At this stage, it is difficult to identify the level of importance for each factor and further research into this area will be a worthwhile study. If the relative importance of each factor could be determined, then this would increase the reliability and validity of the scoring index. A suggested method of identifying the importance of each factor would be to follow a route similar to the one taken by Barsby and Schwarz (1989). In formulating a criterion for assessment of Cobalt-Chromium castings, the authors created a list of the most important features of a casting by conferring with colleagues who were experienced in this field. These features were then scored on a scale of one to ten in order to give each feature an order of importance. As well as speaking to colleagues, surveys could be sent out to hospitals and practices all over the UK in order to generate a larger study population.
5.11 Further research

This section will look into further research that could be carried out in relation to this investigation.

As acknowledged in this investigation, none of the scanning methods tested can produce a scanned surface of a dental study model in a feasible amount of time. It is also clear that all of these scanners and their software carry a large price tag which places them out of reach for most dental environments, whilst two out of the three systems requires a dedicated room, taking up valuable space. There is also the element of having to train up a dedicated operator, which will cost more time and money than it may be worth. A possible solution to this and an area worthy of further investigation would be to evaluate the possibility in terms of reliability, validity, accuracy and feasibly of running a central place of storage to which dental surgeries, hospitals and laboratories could send all their dental study models for them to be scanned and stored. If all these qualities were satisfied then such a system would solve the identified problems of using three-dimensional scanners as an alternative method for the storage of dental study models.

Another area in need of further investigation is the possibility of using the data acquired from the three-dimensional scanners to reproduce a physical three-dimensional model. It has been noted that if time was not a limiting factor in this investigation then this would have been the route that this investigation would have taken as it is essentially the next logical step in the research towards the use of three-dimensional scanners in this manner. The storage of the dental study models is one thing but as revealed in a survey by McGuiness and Stephens (1991), specialist
practices and hospital clinics require the availability of up to 200 sets of study models each day. Therefore, the possibility of being able to reproduce the scanned study models when required would be a definite advantage of this alternative method of storage. Williams et al (2004) have already demonstrated that scanned data can be successfully used to produce a physical plastic shape of a framework design for metal partial dentures using a rapid prototyping. Therefore, it would be interesting to establish whether the scanned data obtained from these three-dimensional scanners can be used to produce an acceptable plastic model of the original dental study model.

From the research carried out in this thesis it is clear that there is limited knowledge on how dental study models are used after treatment. What are the tolerances required for research purposes? The specific uses of these models are unclear and there are no guidelines relating to what dental study models should adhere to such as the tolerances required for research purposes and what kind of detail is required for litigation. If a criterion was developed which detailed the features that study models must contain, then this would make assessing systems of storage not only easier but also more reliable. Therefore further research into this area would be highly recommended.
6. Conclusion

This thesis was undertaken to compare the accuracy of three types of three-dimensional scanners for recording patients' study models and the ease of use of each scanner. It was proposed that such a method could be used as means of storing dental study models.

In comparing the accuracy of the three types of scanners, manual measurements taken from the sample set of dental study models were used as a benchmark. Statistics showed that from repeated measurements manual measurements provided the most reliable data achieving a C.V. for measurements within landmarks of 0.03.

Out of the three scanning systems, it was not possible to identify one system that performed the best in all areas. In terms of ease of use, the touch probe scanner proved to be the easiest to master, which was mainly due to it being fully automated after the initial set up and the training course that accompanied the scanning system upon purchase. The touch probe scanner was also the best in terms of space and required the least operator’s time. The structured light scanner was the most accurate as all of the average landmark measurements were < ±0.5 mm than those of the manual measurements, the level of accuracy that was set to be acceptable from research into the factors which effect the accuracy of study models. It also produced the highest quality of scanned data and the most reliable repeated measurements out of the three scanners achieving a C.V for measurements within landmarks of 0.10 and 0.12 for the upper and lower models respectively. As the structured light scanner performed well within the tolerances established in this thesis, it possible that a smaller, less accurate version of this type of system would produce data that was still
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within these tolerances, whilst being more cost effective and quicker, thus adding to its feasibility.

The laser scanner performed the worst out of the three systems on test and was only best for the speed of the scan achieved as it required the least overall time.

Five limiting factors were identified in this investigation, these being time, the variation of each type of scanner used, the software, the operator and the scoring index devised.

The scoring index has been acknowledged to have the most influence on the interpretation of the results from this thesis, as the majority of the final findings were based on this scoring system. Although the scoring index designed fulfilled the requirement of providing a quick overview of each system in this thesis, it was based on basic criteria, which will require updating to more specific, in depth criteria in order for it to be used as a stand-alone method of comparing three-dimensional scanning systems in the future.

Future research into using the data produced from each of the scanners tested to reproduce a physical three-dimensional model would be a worthwhile follow up to this thesis. This would make it possible to determine whether or not the physical models produced could be used as a substitute to the original study models it has replaced, thereby providing the full advantage that three-dimensional scanning has over previous techniques.
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Bell et al (2003) concluded in their study that three-dimensional imaging could be used to reduce the problems of mass storage of dental study models. The results from this thesis illustrate that the level of accuracy and reliability required to obtain a scanned surface that can be stored for further reference is available at this present time. However, none of the systems were fast enough or at an obtainable price to make them a feasible solution to the mass problem of study model storage in dental hospitals and practices. Nevertheless, with the rapid advancement in technology it will only be a matter of time before a workable system is made readily available.
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9. Appendix

Appendix i: The Co-efficient variation ratio – Within landmarks

Note: The largest C.V of each set has been highlighted in red.

### Upper left Back-Incisor

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Francis Alimohamed

**Average C.V. for Upper Arch**

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Appendix ii: The Co-efficient variation ratio – Across landmarks & Student t Test – P value

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**P value** 0.695920949

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</tr>
<tr>
<td>Lower Right Base-molar</td>
<td>24.26</td>
</tr>
<tr>
<td>Lower Across Arch</td>
<td>41.06</td>
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</tbody>
</table>

### Appendix iii: Student t Test – t value

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Correlation</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1 manual &amp; strulight</td>
<td>14</td>
<td>1.000</td>
<td>.000</td>
</tr>
<tr>
<td>Pair 2 manual &amp; touchprobe</td>
<td>14</td>
<td>1.000</td>
<td>.000</td>
</tr>
<tr>
<td>Pair 3 manual &amp; laser</td>
<td>14</td>
<td>.997</td>
<td>.000</td>
</tr>
</tbody>
</table>

### Paired Samples Statistics

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>N</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1 manual</td>
<td>34.6257</td>
<td>14</td>
<td>12.27475</td>
<td>3.28057</td>
</tr>
<tr>
<td>Pair 2 strulight</td>
<td>34.8221</td>
<td>14</td>
<td>12.23447</td>
<td>3.26583</td>
</tr>
<tr>
<td>Pair 1 manual</td>
<td>34.6257</td>
<td>14</td>
<td>12.27475</td>
<td>3.28057</td>
</tr>
<tr>
<td>Pair 2 touchprobe</td>
<td>34.5957</td>
<td>14</td>
<td>12.27375</td>
<td>3.28030</td>
</tr>
<tr>
<td>Pair 1 manual</td>
<td>34.6257</td>
<td>14</td>
<td>12.27475</td>
<td>3.28057</td>
</tr>
<tr>
<td>Pair 2 laser</td>
<td>34.1621</td>
<td>14</td>
<td>12.57113</td>
<td>3.35977</td>
</tr>
</tbody>
</table>

### Paired Samples Test

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1 manual - strulight</td>
<td>-1.9643</td>
<td>.20307</td>
<td>.05622</td>
</tr>
<tr>
<td>Pair 2 manual - touchprobe</td>
<td>.03000</td>
<td>.28968</td>
<td>.07747</td>
</tr>
<tr>
<td>Pair 3 manual - laser</td>
<td>.46557</td>
<td>1.03043</td>
<td>.27539</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Lower</th>
<th>Upper</th>
<th>t</th>
<th>df</th>
<th>Sig (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1 manual - strulight</td>
<td>-3.3769</td>
<td>-.07469</td>
<td>-3.494</td>
<td>13</td>
<td>.004</td>
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<tr>
<td>Pair 2 manual - touchprobe</td>
<td>-1.3737</td>
<td>.19737</td>
<td>.387</td>
<td>13</td>
<td>.705</td>
</tr>
<tr>
<td>Pair 3 manual - laser</td>
<td>-1.5138</td>
<td>1.05852</td>
<td>1.683</td>
<td>13</td>
<td>.116</td>
</tr>
</tbody>
</table>
Appendix iv – Commercial company’s first attempt

Upper study model

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across arch</td>
<td>43.17 43.24 43.17 43.17</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Lower study model

<table>
<thead>
<tr>
<th>Landmark</th>
<th>Measurement</th>
<th>STDEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across arch</td>
<td>41.19 41.36 41.25 41.42</td>
<td>0.10</td>
</tr>
</tbody>
</table>

There were no obvious anomalies present in the data. However, the standard deviation for the across arch measurement of the lower study model shows that there is a fair amount of variation between the four results, from 41.19 mm to 41.42 mm.

Scanned Data Quality

Figure 9.1 Touch probe 1st attempt - Upper Cast
Figure 9.2 1 Touch probe 1st attempt - Lower Cast

Percentage of data coverage

Upper surface

\[
\frac{3322 \text{ mm}^2}{12741 \text{ mm}^2} \times 100 = 26\%
\]

- 180 -

MPhil
Lower surface

\[
\frac{2160 \text{ mm}^2}{12338 \text{ mm}^2} \times 100 = 18\% 
\]

Data coverage of 26% for the upper and 18% for the lower clearly illustrates that a majority of both study models are missing from the surfaces produced by the scan.

Surface condition

Overall, a stippled effect is evident both the upper and lower surfaces, along with patches where noise is present. A line, which runs along the gingival of the posterior teeth and ¼ of the way up the anterior teeth, is present on both the upper and lower surfaces. Patches of data are missing along this line.

Topology

Figures 4.4 and 4.5 clearly show that the bases of both study models have not been included in the scan, which acts as a vital measurement landmark. The remaining landmarks on the surface of the upper study model are present. However, a section of the right incisor landmark is missing. A closer look at the landmarks present on the molars reveals that there are one or two small pits present on the horizontal planes whilst the vertical planes appear rough.

The surface of the lower study model is also missing most of the lingual region as well as a good proportion of the measurement landmark on the central incisors. The characteristics of the upper molar landmarks are also present on the lower surface.
Appendix v - Initial accuracy criteria

The accuracy of the scanning method is determined by how close the measurements of the landmarks on the scanned images are to the manual measurements. Factors such as tooth mobility in their sockets - a maximum of 0.03 mm (Parfitt, 1960), the dimensional stability of impression material - up to 0.68 mm variation (Cohen et al, 1995)) and the expansion of die stone - 0.05-0.15% (O’Brien and Ryge, 1978) suggest that an acceptable tolerance value for scanner accuracy is justified. Agreeing with the findings of Bell et al (2003), a difference of < ±0.5 mm between the average result for each measurement landmark compared to that of the scanning method has been taken to be not significant. The number of times a difference of < ±0.5 mm is achieved is placed over the number of measurement landmarks – 14.

A rating can be increased if an average measurement is achieved by a scanning method that is the same as that of the manual method. A rating can be further increased if an average measurement gained by a scanning method is the closest out of the three scanning methods to the manual method for that measurement landmark.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria</th>
<th>Rating</th>
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</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>14/14</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>10/14</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>7/14</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4/14</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1/14</td>
<td>1</td>
</tr>
</tbody>
</table>
### Bonus ratings

<table>
<thead>
<tr>
<th></th>
<th>Every result equal to manual method</th>
<th>+1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Closest to the manual method for each measurement landmark</td>
<td>+1</td>
</tr>
</tbody>
</table>

*Scoring index – Initial accuracy criteria*

### Appendix vi – Cost of equipment

#### Structured light

- Steinbichler Comet 250: £60000.00
- Innovmetrics Polyworks IMAlign – Emailed
- AliasWavefront Spider – Emailed
- Computer: £999.00

**Total Cost**: £60999.00 + Inc VAT.

#### Touch Probe

- Renishaw Cyclone 3d Scanner inc Tracecut: £37,600.00
- Computer: £999.00

**Total Cost**: £38,599.00 Inc VAT.

#### Laser

- Minolta V 910 with 3 lenses and PET software 3d Scanner: £26,348.00
- Small turntable set: £3,587.00
- Tripod set: £1,300.00
- Easy3Dscan software: £3,482.00
- Computer: £999.00
- Rapid form 2004: £3879.00

**Total cost**: £42432.78 Inc VAT.
10. Word Count

Abstract: 292
Introduction: 901
Literature Review: 10625
Method: 8658
Results: 4846
Discussion: 8224
Conclusion: 634

Total: 34180

Signed: [Signature]
Date: 10/03/06