

Simple smartphone applications for superimposing 3D imagery in forensic dentistry

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ABSTRACT

Background: Forensic dentistry identification commonly involves using dental cast models as ante-mortem data. Here, dentists generally send the pictures as well as the dental records. However, in recent times, dentists – especially orthodontists and prosthodontists – are using 3D scanners in view of reducing the space for cast model storage as well as sending the 3D imaging for fabricating clear aligners and other items such as crowns and bridges. This new trend means data transmission and viewing has become more complicated since sophisticated laptops or personal computers are generally required. For more practical use, smartphones would be a better option, meaning various simple ideas for viewing 3D data must be explored. Furthermore, the conclusions must be evaluated in terms of the validity for forensic dentistry use. **Purpose:** To evaluate a number of smartphone applications that are simple, user friendly, scalable and capable of the measurement and superimposition of 3D imaging data. **Review:** Standard tessellation language (STL) is one of the 3D scan file formats that is also useful for 3D printing. Recently, several applications for 3D viewing have been made available for iPhones (iOS) and Android-based devices, which are able to view STL files. However, they have all received both positive and negative reviews in terms of various applications, including forensic dentistry, and they thus require further evaluation by forensic odontologists. **Conclusion:** Each application has advantages and disadvantages; however, in our experience as forensic odontologists, the CAD Assistant, exocad and Adobe Photoshop Mix, which are available for iOS and Android devices, are preferable for forensic dentistry needs.

Keywords: 3D imaging; superimposition; smartphone; forensic dentistry

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INTRODUCTION

The implementation of advanced computer-aided dentistry and computer-aided manufacturing technology (CAD/CAM) has been widespread over the past thirty years since the field of modern clinical dentistry demands that patients must receive the highest quality treatment.¹ CAD has been used to digitise oral and dental structures for the virtual design of both simple and complex prosthetic units.² Meanwhile, forensic dentistry, a new field in the arena, requires individual unique identification when confirming the identity of individuals involved in a crime or death. The field also requires the highest possible accuracy to

satisfy the logistical and emotional needs of all parties involved. However, a number of confounding factors can come into play here, including the relative experience and expertise of the individual performing the comparison, the availability, quality and age of the records, and the post-mortem damage.³

Frequently, post-mortem (PM) identification involves comparing the before death (ante-mortem, AM) dental records (radiographs and dental cast models) with the teeth of the deceased individual, while injury analysis, or thanatology, involves examining the bone fragments or contusions in relation to various weapons or known injuries. A scientific and objective comparison using

advanced technology would strengthen the validity of forensic dentistry. Within the forensic sciences, CAD/CAM technology has numerous benefits for procedures such as age estimation, bite-mark or lip-print analysis, injury analysis and PM identification. Moreover, CAD/CAM technology can also be used to create three-dimensional (3D) crime scene reconstructions.^{4,5}

Since the 1700s, dental impression techniques using specific impression materials have been used to record the 3D morphology and measurements of both hard and soft dental tissues. However, changes in the volume of the impression materials and the expansion of the dental stone can lead to distortion, which can affect the precision of prosthetic procedures.⁶ In order to resolve these issues, digital impressions using intraoral scanning (IOS) have been developed in the field of dentistry.⁷ The application of the IOS devices in dentistry falls in line with the development of CAD/CAM technology. Currently, IOS and CAD/CAM technology make treatment planning, case consultation and the communication with dental laboratories far easier while reducing chair-time and the amount of storage required.^{7,8}

However, the widespread use of digital data and data transmission requires good access to the internet, especially during the disaster victim identification (DVI) process in victim identification centres, which is not always possible in developing countries or remote locations. The field of DVI must consider this issue when the centres plan their strategy for handling AM data.⁹ Exporting 3D data for viewing on other devices such as laptops or PCs, as well as small portable devices such as tablets or smartphones, can be an issue since the apps required to view the real 3D data often cannot be installed on these devices or perhaps require payment. In addition, these apps may involve lower quality, can be non-user-friendly and can include too much advertising as well as other unexpected disadvantages. Moreover, there are different apps for the iOS and Android systems, which may vary in terms of picture quality depending on the system used.¹⁰

However, there do exist a number of smartphone apps that may be useful in forensic dentistry, including CAD AssistantTM and exocadTM for viewing, and Adobe Photoshop MixTM for superimposing. Nonetheless, there is a lack of reviews or reports on their use in forensic dentistry within the relevant body of literature. In view of this, obtaining the individual experiences of forensic odontologists who have already used these apps would undoubtedly be beneficial.

With this in mind, this review is aimed at evaluating specific apps for both iPhones and Android devices that are deemed as simple, user friendly and scalable and which are appropriate for the measurement and superimposition of 3D imaging data for forensic dentistry. The evaluation is based on the operational procedure and involves direct comparisons with the actual images captured by a 3D intraoral scanner (3Shape TRIOSTM).

Digital Imaging in Forensic Odontology

The forensic sciences are multidisciplinary fields that require both cooperation and coordination among police officers and other law-related officers, forensic experts such as forensic pathologists, forensic anthropologists and forensic odontologists, etc.¹¹ Meanwhile, forensic dentistry, or forensic odontology, is the implementation of dental science within the field of criminal and civil law, working in compliance with police organisations operating under the criminal justice system. Forensic odontology plays a significant role in identifying criminals since, while the status of an individual's teeth may change during their lifetime, the combination of decayed, missing and filled teeth can still be effectively measured and compared at any time.^{5,11}

Forensic dentistry encompasses a number of areas, including human remains identification, mass disaster body identification, the assessment of bite marks and lip prints, and age estimation, while it is often used in child-abuse cases.⁵ The four types of violence outlined by the World Health Organization, namely, physical, sexual and psychological violence and neglect, can be manifest in the orofacial region, which is the domain of dentists and forensic odontologists.¹¹ Today, while advanced photography and scanning techniques are used in forensic odontology, the invention of 3D printing has signalled huge advances in areas such as bite-mark analysis.¹²

The benefits of digital imaging technologies for forensic odontology include computerised dental record systems, which cover both dental treatments and odontograms and which have replaced the physical dental record systems. Conventional X-ray images, which include orthopantomography (OPG) images, are captured as digital images in developed countries via computed tomography (CT), cone beam computed tomography (CBCT) and intraoral 3D scanning.¹³ PM data should also be digitalised wherever possible, while processing X-ray images using chemicals should be avoided since the imagery must be directly digitised for storage to prevent any possible quality issues.¹³ According to Javaid *et al.* (2019),¹⁴ errors may occur when the dentist labels the X-Ray film with the patient's name or when the forensic odontologist labels a film with the victim's identification number after processing. The major benefits of digital data include that they can be stored for long periods of time on mass storage technologies such as cloud storage systems, which can be routinely backed up.¹⁴

Other advantages of digital data include that it can be rapidly transmitted and received with identical characteristics and no loss of resolution or quality, meaning, unlike with X-ray film, no subsequent scanning is required.^{13,15,16} Neither the original films nor the dental models are sent to the DVI centres, with the original copies remaining at the dental office to ensure the records cannot be lost during the DVI process. The use of digital dental PM data will ensure it can be inputted directly into computer

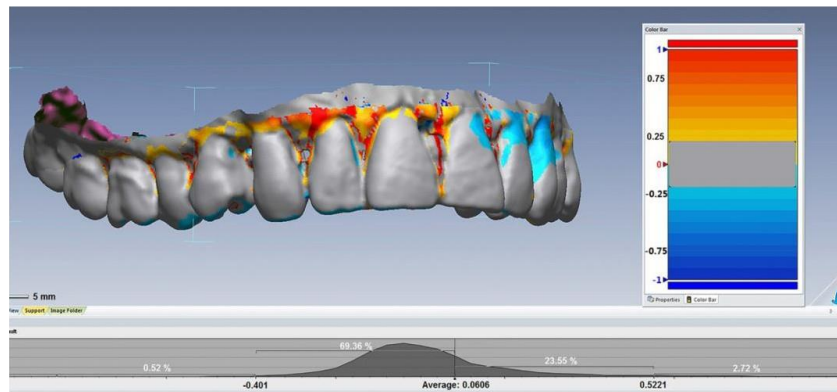


Figure 1. Three-dimensional (3D) superimposition. The PM surface is superimposed on the ante AM surface. (Adapted from Forrest A: *Forensic Odontology in DVI: current practice and recent advances*¹⁷).

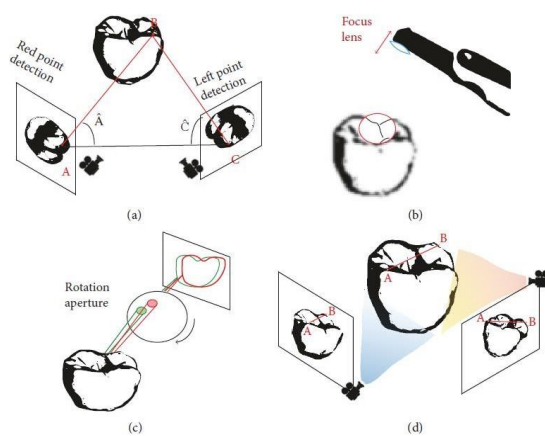


Figure 2. Determining the distance to the object. (a) Triangulation: the BC can be determined according to the formula $BC = AC \times \sin(A) / \sin(A+C)$, (b) Confocal: distance to the object is determined according to the focal distance, (c) AWS requiring a camera and an off-axis that moves on a circular path around the optical axis and produces a rotation of interest points, (d) Stereophotogrammetry is a technology that generates files via algorithm-based analysis.⁹

applications such as DVISys, which will help prevent any transcription error. As Forest¹⁷ declared, one of the most sophisticated aspects of 3D laser scanning in forensic dentistry is the AM/PM superimposition (Figure 1).

3D Laser Scanning

The 3D laser scanning equipment senses the shape of an object and accumulates the data that describes the location of the object's outer surface. Such technology is useful for a large number of industries, including separate and process manufacturing, construction, utilities, law enforcement, archaeology, governance and entertainment. In the past two decades, laser scanning technology has evolved into being an important surveying technology for the acquirement of 3D information.¹⁴

3D laser scanners operate in terms of three main methods: time-of-flight, phase shifting and triangulation.

Meanwhile, there are three main types of 3D scanners: airborne scanners, terrestrial scanners and hand-held scanners. In addition, advanced technologies in the areas of software processing, data acquisition and user-friendly apps for 3D laser scanning are also being invented on a yearly basis.^{10,13}

Intraoral Scanner Technologies

An intraoral scanner (IOS) is a dental and medical device consisting of a hand-held camera (hardware) attached to a computer with 3D processing software. An IOS is able to capture and record the 3D geometry of an object with high precision. The most widely used digital formats are the open standard tessellation language (STL) models or lock STL file models. STL, which is commonly used in many industrial areas, describes a series of triangulated surfaces where each triangle is defined by three points and a normal surface.⁹ However, the format has drawbacks in that it cannot capture the colour, transparency or texture of dental tissues, which can be captured by other file formats such as the Polygon File Format (PLY). As with any form of image capturing, the cameras require the projection of light to record objects as individual images or videos, which are then collected by the software after the recognition of the points of interest (POI). The first and second coordinates (x and y) of each point are assessed on the image and the third coordinate (z) is then calculated depending on the object's distance (Figure 2).^{9,10}

In order to acquire the shape of a 3D object digitally, 3D scanners are divided into two types: contact and non-contact, while the latter can be further divided into two main categories: passive scanners and active scanners.^{10,13} The 3D contact scanners are generally operated on a fixed platform and often contain a probe positioned at the end of a movable mechanical arm.¹³

In forensic dentistry, intraoral scanners such as the 3Shape TRIOS are categorised as active scanners that release or emit light or some form of radiation and then detect its reflection to probe an object or environment. The possible types of emissions include x-ray, ultrasound or light.⁹ Other categories of 3D laser scanners operate in

terms of time-of-flight, phase shift or laser triangulation, methods that are generally used separately but can also be used together to create a multipurpose scanning system.¹³

Standard Tessellation Language Files in 3D Scanning

The STL file format was developed by Charles Hall in 1987 to support his stereolithographic 3D printer. The file extension (.STL) is an abbreviation of 'stereolithography' or an acronym for standard triangulation language or standard tessellation language. At present, it remains the leading file format used to transmit a 3D model to a 3D printer via a computer¹³ and is the most widely used file type for IOS. The STL file defines the 3D model's surface using a group of linked triangles to recreate the surface geometry. These small triangulations construct a surface that results in the faceting of the 3D model.

While more recent file types can create more detailed data, the main advantage of STL is its simplicity. In fact, STL is based on open-source coding and is widely available, which means anyone can review, improve or share an STL file.¹⁷ Other advantages include the universal format that allows for manipulation using almost every type of CAD software program and 3D printer. In addition, its vector-based (triangulation) graphics provide scalability without any loss of resolution. Thus, the STL file format is arguably the most important aspect of the 3D printing procedure; however, it only transmits geometric structures and not colours.¹⁸ Furthermore, a digital model requires some form of preparation such as smoothing prior to the 3D printing, since the software supplied with the 3D printer may not perform all manipulations completely, meaning other CAD/CAM software program are required.^{19,20}

3D Intraoral Scanner Comparison

CAD/CAM technologies in dentistry were introduced in 1971 to obtain 'optical impressions'. Following its continuous development, CAD/CAM technology has been applied in prosthetic and orthodontic procedures since the 1980s. The first IOS that was commercialised within the dental market was the CEREC system (Sirona Dental System GMBH, Bensheim, Germany).²¹ Various manufacturers have subsequently developed IOS systems with different performance properties for generating digital images (e.g. iTero, Align Technologies, San Jose, CA, 2007 and 3Shape TRIOS, Copenhagen, Denmark, 2010).¹⁰

iOS and Android

According to Asokan,²² mobile phones have become a major part of human life. Indeed, almost every daily activity would appear to involve some form of smartphone technology, which has gradually replaced many of the functions of PCs. Two of the most widely adopted operating systems in the current era are the iOS and Android systems, the former developed by Apple and the latter by Google. However, Sahani²³ noted various differences while using both operation systems in terms of both the system and the attendant security. Elsewhere, Mohamed²⁴ noted the benefits of using the Android system, an open source-

type system, which include the prices, the wide variety of available devices, the customisability and the widget features. For certain, it allows for greater customisation than the iOS system. However, iOS provides more functionality, that is, higher speeds, less delay, and less buffering, since the chance of filling Apple phones with unnecessary third-party launchers or customisation apps is reduced.^{22,23}

Applications for 3D Viewing and Superimposition with iOS and Android

The minimum requirements for smartphone applications that can be used in forensic dentistry include the capacity for 3D image viewing, measuring and superimposition, while scalability is also a factor. Several STL-based applications are available for iOS and Android smartphone systems. In terms of iOS, the application can be downloaded via an app store, while in terms of Android, Google Play is the required platform.²² In this article, we, as forensic odontologists, choose several applications that best suit our daily needs, that is, they are free and user friendly (i.e. it is easy to search for and upload files). In addition, we also choose applications that can superimpose AM/PM STL data images. The chosen applications are CAD Assistant, exocad, and Adobe Photoshop Mix.

In order to allow for storing file data obtained via an IOS (3Shape TRIOS) from a patient on a PC, the file has to be saved three times, in DCM, STL, and 3ox formats.⁵ Subsequently, the STL data is transmitted to the Android and iOS smartphones – which, in this case, are the Samsung Galaxy S8+ and the iPhone XR – via USB on the go (OTG), before they are opened via CAD Assistant and exocad for 3D viewing.

CAD Assistant

The open cascade CAD Assistant is an offline 3D viewer and converter application for both iOS and Android system operations. The supported file formats are CAD and mesh data formats (STL, STEP, and OBJ). It has several advantages over its competitors, including its simplicity, its measurement ability and its file size handling ability (up to 50 MB). However, devices with a low-range graphic processor can take some time to open the files.²⁵ An illustration of an iOS-exported STL file using the 3Shape TRIOS is presented in Figure 3. In order to have an accurate view, a true horizontal position of the occlusal plane of the dental model 3D image makes it easier to achieve perfect superimposition, which can be achieved by tapping the view option buttons at the front and bottom right. The view option button located at the bottom right (Figure 4) is used for zooming in and out using the thumb and index finger.

Adobe Photoshop Mix

Adobe Photoshop Mix is a creative photo editor. It is able to cut out, combine and create images. The functions of this app include combining, enhancing, sharing, blending, upright viewing, filling, and many more. It is available for PCs, tablets, and smartphones. The benefits of this application include that it is a freeware, powerful photo

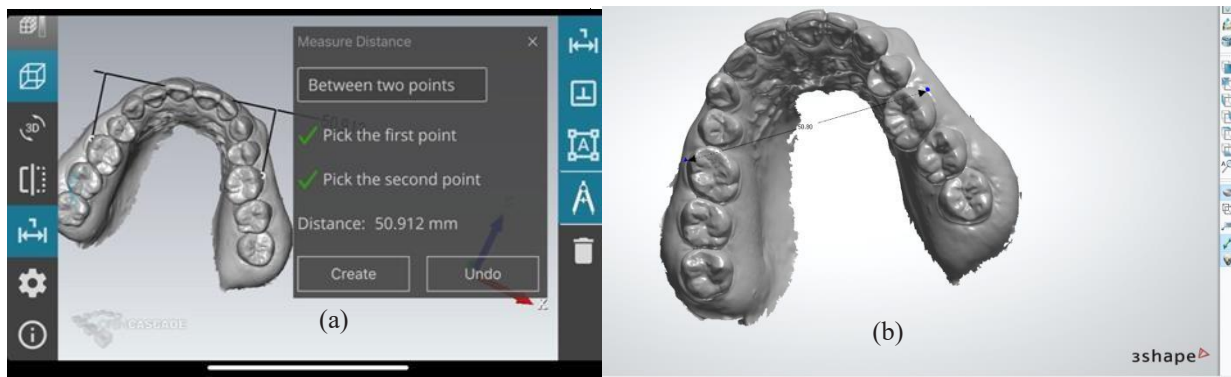


Figure 3. (a) CAD Assistant viewing intermolar distance of 3D STL data = 50.912 mm on a smartphone (b) 3Shape TRIOS dental scanner viewing intermolar distance = 50.80 mm on a laptop.

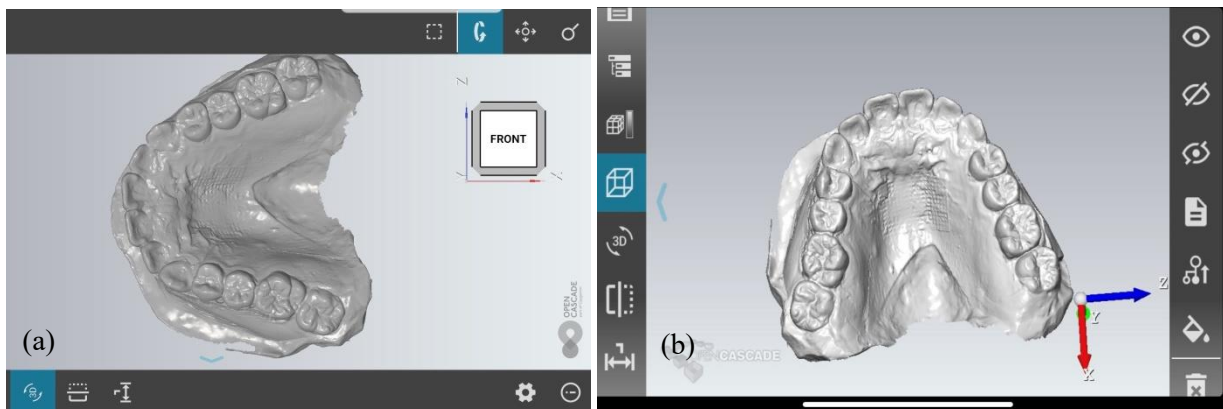


Figure 4. Flat shaded display mode on (a) Android Samsung S8+ and (b) iOS iPhone XR.

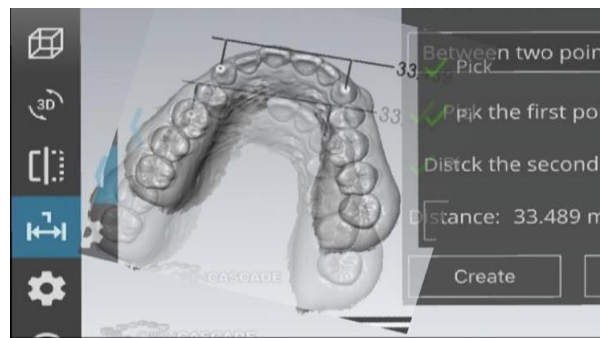


Figure 5. Blending of two screenshots from CAD Assistant.

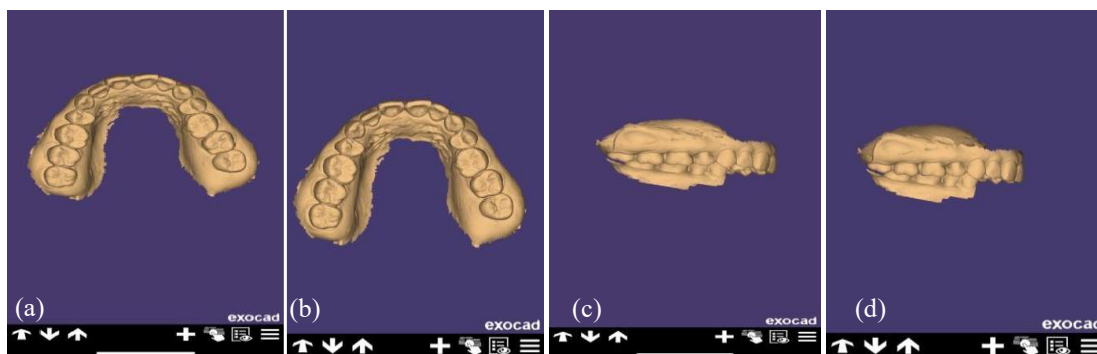


Figure 6. 3D STL data viewing on exocad smartphone app. (a) Maxillary scan on iOS, (b) maxillary scan on Android, (c) combined two-file occlusion on iOS, (d) combined two-file occlusion on Android.

editor (user can add more than one photo) and that it has a blending ability.²⁶ Blending is a technique that allows users to combine more than one picture as well as adjust the contrast, transparency and visibility. The app is also capable of superimposing two images of, for example, teeth model scans (Figure 5).²⁷

Exocad

While some applications are not compatible with PCs, exocad is available for PC users. This application was built by exocad GmbH and was specifically designed for the digital field of dentistry. According to the exocad website, users are able to design implants, bars, models, full denture models, virtual articulators and jaw-motion models. While this cannot all be done using a smartphone, the benefit of using a smartphone is that users can add more than one file to combine each fragment into an occluded model for matching jaw fragments (Figure 6).²⁸

DISCUSSION

Regarding the accuracy of iOS for duplicating tooth preparations for prosthetics and clear aligners in orthodontics, several in-vitro and in-vivo studies have evaluated the system based on various best-fit software configurations of single units to full dental arches.^{10,21} Here, Muller *et al.* (2016),²⁹ found that the difference in scanning approach among the iOS systems resulted in statistically significant differences in accuracy. Elsewhere, Gimenez *et al.*³⁰ revealed certain differences that resulted in bias when comparing the results obtained by both expert and non-expert users when scanning dental implant models. Meanwhile, other research reported that certain varieties of material (e.g. gypsum and polyurethane) are almost perfect diffusers, while metals, which have a higher level of specular reflection, can affect the iOS accuracy.³¹ However, these conditions are not the concern of forensic odontologists since the differences were only in μm (micro metres).

The benefits of using iOS as the operating system include, according to Asokan,²² the battery life, the security and the quality of the apps. While Apple systems do not provide as good multitasking efficiency as Android systems, the battery life is shorter in the latter, while multitasking using mobile devices is not as easy as when using a desktop. According to Sahani,²³ iOS has a more stable and secure system since it is more private unless it has been hacked. The apps provided in iOS are among the best in terms of quality and quantity. In addition, according to Mohamed,²⁴ the iOS operating system is so polished that when the same app is running on both operating systems, the quality is much higher using the iOS system. In fact, the differences in the iOS and Android working systems result in the differentiation between the applications that can run on each system. Here, while some can be run on either system, many can only be run on one or the other.^{22,23}

The iOS and Android operating systems have their own applications, with some able to be operated on both systems and others not. The CAD Assistant, Adobe Photoshop Mix and exocad are three 3D viewer apps that can be used on both systems.

Linear measurement, superimposition and occlusion viewing are arguably the most important aspects in forensic dentistry. CAD Assistant is capable of measuring linear distances. Here, the important point is the precision, which depends on the screen itself (zoom and sensitivity) and the operator. Park *et al.* (2015)³² used a stylus pencil to click the smartphone's screen in order to increase the precision of the measurement. However, the difference in measurement between smartphones and PC is very slight.³² In our experience, this program can be considered as accurate for forensic dentistry needs because the difference in the app imagery compared with the 3D scanning imagery is negligible (TRIOS = 50.8 mm, CAD assistant = 50.912 mm in). In order to more accurately compare two models, we can use a program called CloudCompare, which is 3D point cloud processing software. It can compare two STL data formats, but is only available for PCs.³³

The benefit of Adobe Photoshop Mix relates to superimposition, which involves matching two STL images. This is achieved by manipulating the second dataset to match the size of the first before superimposing both sets. First, both STL datasets should be set up perpendicularly in CAD Assistant by pressing the front view option button before taking a screenshot (Figure 4). Then, the first and second screenshots are added and then blended (Figure 5). While both CAD Assistant and exocad are able to view STL file types, the occlusion viewing in the latter allows for combining several datasets into a occlusion model. Meanwhile, Adobe Photoshop Mix is more advantageous in terms of its superimposition capability for matching AM and PM scan results. Therefore, all the applications are good and are useful for the forensic dentistry field.

Based on our experience of the superimposition of 3D imagery using the 3Shape TRIOS, the sequence of data processing should be as follows: converting the original 3D image scan file to a STL file, setting the CAD Assistant to perpendicular view by tapping on the front view option, ensuring the size comparison with the original by choosing the measurement points using CAD Assistant (shown on the screen), using the screen shots tool to capture the last view on the screen, and using Adobe Photoshop Mix to compare the AM/PM image by zooming in or out and rotating the image.

Overall, it can be concluded that the STL files of AM and PM images can be rapidly transmitted with ease, accuracy and detail. In the future, the forensic odontology undertaken in DVI centres will increasingly depend on 3D imaging data captured via CT and 3D scanning, and newer forensic odontologists should be more experienced in using this digital imaging technology and will be quickly become accustomed to using it in practice on a daily basis. Based on our experience in forensic odontology, the CAD

Assistant, exocad and Adobe Photoshop Mix apps, which are available for both iOS and Android systems, are the best options. However, further research should be conducted to ensure global acceptance.

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