Title:

Accuracy of a novel prototype dynamic computer-assisted surgery system

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Running title:

Accuracy of a novel prototype dynamic CAS system

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Key words:

computer-guided, computer-aided, navigation, dental implant, stereolithographic guide, static guide, accuracy

Abstract

Objectives: To implement and evaluate the accuracy of a prototype dynamic computer-assisted surgery (CAS) system for implant osteotomy preparation and compare its accuracy versus three commercial static CAS systems and the use of an acrylic stent.

Material and Methods: Eight osteotomies were prepared in radiopaque partially edentulous mandible and maxilla typodonts. After cone-beam CT acquisition, DICOM files were imported into a prototype dynamic, and three static CAS systems (NobelClinician, Simplant, and CoDiagnostiX). Implant placements were planned to replicate the existing osteotomies and respective guides were requisitioned, along with one laboratory-made acrylic guide. The 8 osteotomies per jaw were transferred to one typodont pair mounted in a manikin in a clinical setting and the process was repeated for 4 additional pairs. The 80 (2 jaws x 8 holes x 5 pairs) osteotomies were filled with radiopaque cement in-between the testing series. Three clinicians experienced with the use of the static CAS softwares used in this study prepared each 400 (80 holes x five modalities) osteotomies. One clinician repeated the experiment twice, resulting in a total of 2000 (5 clinicians x 400) osteotomies. The lateral, vertical, total and angular deviations of the actual versus the original osteotomies in the master typodonts were measured using stereo optical tracking cameras. Linear regression statistics using generalized estimating equations were used for comparisons between the 5 modalities and omnibus chi-square tests applied to assess statistical significance of differences.

Results: The prototype dynamic CAS system was as accurate as other implant surgery planning and transfer modalities. The dynamic and static CAS systems provide superior accuracy versus a laboratory-made acrylic guide, except vertically. Both dynamic and static CAS systems show on average less than 2 mm and 5 degrees error. Large deviations between planned and actual osteotomies were occasionally observed, which needs to be considered in clinical practice.

Conclusions: The prototype dynamic CAS system was comparably accurate to static CAS systems.

Implant-retained prostheses are today a treatment modality with a highly predictable outcome (Pjetursson et al. 2007). Poor implant positioning, however, compromises esthetics and function and increases the risk for biomechanical overload. An important premise for the long-term success of implant supported prosthetic restorations is proper implant position. Presurgical planning combined with use of a surgical guide during the placement of dental implants is therefore encouraged. Surgical guide techniques based on new computer technologies enable three-dimensional image reconstructions and interactive therapy planning; the latter leading to fabrication of surgical guides derived from computer tomography (CT) and computer-assisted surgery (CAS) (Fortin et al. 1995).

Static CAS modalities offer a reliable transfer of the planned implant locations. The intra-operative handling of surgical guides is uncomplicated and there is relatively easy co-ordination of procedures between guide planning, manufacturing and surgical application without the need for additional expensive equipment. However, there are also some limitations. The stability of the surgical guides, which are placed on a few remaining teeth, directly on the mucosa or the crest of the bone, is critical. Placement of implants in the posterior zone may also present a problem if the opposing dentition limits the space to insert and use the surgical guide. (Jung et al. 2009; Schneider et al. 2009; de Almeida et al. 2010; D'Haese et al. 2012; van Assche et al. 2012; Hultin et al. 2012).

Dynamic CAS is a relatively recent emerging field in the dental implant field (Brief et al. 2005; Mischkowski et al. 2006). Position tracking markers, also known as fiducial markers or simply fiducials, are attached rigidly to the anatomy being operated on as well as to the surgical instruments and the spatial location and orientation of the fiducials is continuously recorded during the surgical procedure in real-time, using some form of sensors (Ewers et al. 2005; Miller & Bier 2006). Dynamic CAS systems have been used primarily in neurosurgery and orthopedic surgery, and have been based on electromechanical, ultrasound, electromagnetic, optical or combined techniques.

Dynamic CAS systems exhibit acceptable *in vitro* accuracy, but the intraoperative precision can be less predictable. Furthermore, the time-consuming set up procedures, the complicated user interface, and problems with placement of the external monitors and clear line of sight have not led to wide acceptance of this modality in the field of craniofacial surgery (Hassfeld, et al. 2003). Relatively high purchase and maintenance costs of current dynamic CAS systems for dental implant applications may also be an important factor. A new dynamic CAS prototype concept that attempts to address these known drawbacks is currently under development (Claron Technology Inc., Toronto, Canada). Optical tracking cameras are deployed during the actual surgery to provide dentists with cone beam CT (CBCT)-based real-time 3-dimensional guidance during the surgical placement of dental implants.

The primary purpose of this study was to appraise the accuracy of implant osteotomies in a simulated clinical setting using the prototype dynamic CAS system in comparison with osteotomies achieved with stereo-lithographic surgical guides made from three commercial static CAS systems. The null hypothesis was that the accuracy of the prototype dynamic CAS system is not better than commonly used methods for surgical positioning of dental implants in a preclinical setting.

Material and Methods

Master model osteotomies and CBCT registration

Anatomically correct size typodonts with silicone lining specially manufactured for dental implant surgery training purposes (maxilla- A-J F OK K, mandible- A-J F UK K, Frasaco GmbH, Tettnang, Germany) containing three teeth (13, 23, 27 and 33, 37, 43) were used (Fig 1a). The typodonts were duplicated in reversible hydrocolloid (Dupli-Coe-Loid, GC America Inc. Alsip, IL, USA) and poured up in dental stone (Microstone, Whip Mix Corp, Louisville, KY, USA). The stone casts were articulated in a KaVo Protar 5 articulator (KaVo Dental, Charlotte, NC, USA) (Fig. 1b). Acrylic denture teeth (Classic Trubyte, Dentsply International, Milford, DE, USA) were selected and set up in wax on the stone casts to mimic ideal occlusion. The finished dentition set ups were duplicated with irreversible hydrocolloid (Jeltrate Plus, Dentsply International, Milford, DE, USA) and poured up in dental stone. A vacuum foil (Sta-Vac sheet resin 0.020, Buffalo Dental Canada, Cambridge, ON) was adapted to the resulting cast with a vacuum forming machine (Biostar, Perma Laboratories, Brunswick, OH) and a pair of radiographic templates were prepared with radiopaque acrylic material (BiocrylX, Great Lakes Orthodontics Ltd., New York, NY) for the master mandible and maxilla typodonts. The maxillary and mandibular radiographic templates were placed on the master mandible and maxilla typodonts and volume data of the region of interest was acquired by CBCT on a CB MercuRay (Hitachi Medical Systems, Tokyo, Japan) in I mode (FOV = 10 cm), 100 kV and 10 mA.

The mandible and maxilla radiographic templates were duplicated with a laboratory putty matrix (Zetalabor, Zhermack, Badia Polesine, Italy) as outlines for surgical guides fabricated in clear acrylic (ProBase Cold, Ivoclar Vivadent, Schaan, Liechtenstein). The mandible and maxilla surgical guides were designed for optimized locations relative to the planned tooth position in the regions of missing teeth (3 posterior left, 3 posterior right, 2 anterior sites) as dictated by the CBCT radiographs showing the outline of the radiographic template and available bone (Fig. 1c, fig. 1d). The acrylic mandible and maxilla surgical guides were next used to prepare eight parallel osteotomies in the master typodonts without reflecting the silicone lining, imitating a “flapless approach”. Surgical profile drills (Straumann USA, Andover, USA) were mounted in an angulated handpiece and the osteotomies had a depth of 10 mm with a diameter of 4 mm. The master mandible and maxilla typodonts containing the osteotomies were scanned in the CBCT using the same radiographic parameters as described above (Fig. 2).

Surgical guidance modalities

Five different modalities for surgical guidance were tested in succession on 5 pairs of typodonts. The modalities were:

a, A laboratory made acrylic surgical guide,

Three static CAS systems

b, Simplant, (Materialise Dental, Leuven, Belgium);

c, Straumann guided surgery, (Institut Straumann AG, Basel, Switzerland);

d, NobelClinician, (Nobel Biocare AG, Zürich, Switzerland)

and

e. The prototype dynamic CAS system (Claron Technology Inc., Toronto, Canada).

Specific preparations for each modality were:

Acrylic, laboratory made surgical guide

The radiographic templates were duplicated with a laboratory putty matrix (Zetalabor, Zhermack, Badia Polesine, Italy) as outlines for maxillary and mandibular surgical guides fabricated in clear acrylic (ProBase Cold, Ivoclar Vivadent, Schaan, Liechtenstein) (Fig. 3a). The acrylic surgical guide was used to initiate with a pilot drill the location of eight osteotomies. Once initiated, the surgical guide was placed aside and the osteotomies were continued freehand using profile drills without guidance. The operators used implant guiding pins to acquire parallel osteotomies.

Static CAS systems

For the three static CAS systems the radiographic templates were fabricated according to the manufacturer's instructions pertaining to each individual CAS modality described below. Following import of the respective DICOM files the outlines of the 8 osteotomies in the master typodonts were located on the reformatted CBCT images. Eight implants in the regions of missing teeth (3 posterior left, 3 posterior right, 2 anterior) were virtually placed to match precisely the osteotomies before ordering the stereolithographic surgical guides from the respective manufacturers. Upon receipt of the guides the fit was checked on the stone casts and typodonts and, if required, corrected before disinfection and ready to be used in a mannequin in a clinic setting.

Safe SurgiGuide ordered through Simplant

The DICOM files from the CBCT scan were converted to Simplant planner format by the Radiology Department at the University of Toronto, Faculty of Dentistry. The reformatted file was opened with *Simplant Planner Version 14.0* on Windows (Materialise Dental, Leuven, Belgium). The surgical plan and duplicate stone casts were sent to the manufacturing facility and 2x4 tooth-supported *Safe SurgiGuides* were ordered for the maxilla and the mandible to be used with the Straumann guided surgical drills (Ø2.8, 3.2, 3.5, 4.2 mm) (Straumann USA, Andover, USA) (Fig. 3b). The osteotomy procedures were performed with the *Safe SurgiGuides*, acquiring fixed osteotomy positions and angulations with the use of drill keys intended for Straumann surgical drills.

Straumann scan and surgical templates ordered through CoDiagnostiX

*Straumann scan templatse f*or the maxilla and mandible and were manufactured in a local dental laboratory, based on the existing radiographic templates and master stone casts. The radiographic template was connected to the *Straumann TempliX reference plate* with the three reference pins in a *GonyX* device by a local certified dental laboratory. The master typodonts were scanned with the *Straumann scan template* in a CBCT unit with the previous settings. The DICOM files from the CBCT scan were imported by *CoDiagnostiX Version 8* on Windows for implant placement planning, and *Straumann surgical templates* were ordered from the same dental laboratory, who also received duplicate casts (Fig. 3c). Osteotomy procedures were performed using the *Straumann surgical template* following the manufacturer's instructions, acquiring fixed osteotomy positions and angulations with sleeves having a 5.0 mm inner diameter and the use of drill handles for Straumann surgical drills**.**

NobelGuide surgical templates ordered through NobelClinician

The previously optimized tooth setup was duplicated in a local laboratory to produce a radiographic template. Guttapercha points were positioned as markers in the guide for software recognition and scanned with the dual scan protocol in a CBCT unit with the settings described above. The resulting DICOM files from the CBCT scans were imported into *NobelClinician Version 2.1* on PowerMac. Following the virtual treatment planning, tooth-supported *NobelGuide surgical templates* with three fixation pins each were ordered from the manufacturer (Fig 3d). The *NobelGuide surgical template* was secured to the typodont with use of the fixation pins. After stabilization with the fixation pins, the osteotomies were performed through the *NobelGuide surgical template* acquiring fixed osteotomy positions and angulations by fitting the Straumann drill handles intended for Straumann surgical drills into the RP 4.3 guided sleeves, having an inner diameter of 5.02 mm.

Prototype dynamic CAS system

The prototype dynamic CAS system consists of dedicated software (Navident prototype, Claron Technology Inc., Toronto, Canada) that runs on a PC or Apple laptop computer, and tags (trackable attachment prototypes) connected to a handpiece and to a jaw that are tracked by stereo optical tracking cameras (MicronTracker model Hx40, Claron Technology Inc., Toronto, Canada). The software encompasses an integrated planning and guidance application, although the guidance module works also without first activating the planning module. Guidance set up and interaction requires no keyboard/mouse input - the system will configure itself and respond based only on drill motions relatively to the jaw tag. The jaw tag is outside the clinical operating field and attached to a radiograhphic fiducial made from aluminum located in the anterior buccal part. The radiographic fiducial is incorporated in a thin thermoplastic shell designed to be molded over the lower or upper jaw. The tags secured to the jaw (fig. 4a) and to the clinician's handpiece (Fig. 4b) carry an arrangement of circular black/white regions functioning as optical fiducials within the area captured by the stereo optical tracking cameras. The setup enables continuous measurement of pose (location and angle) of the optical fiducials in real time by the dedicated software.

The CBCT examination is done with the patient carrying the radiographic fiducial. The software imports the DICOM data and virtual implant placement planning is done fairly similar to existing commercial static CAS systems. The radiographic fiducial is automatically detected and located in the CBCT images, enabling mapping its pose in the image to be automatically and accurately mapped to its pose during the operation, which is dynamically tracked through the jaw tag that is firmly attached. The position and orientation of the drill tip relative to the optical fiducial on the handpiece tag is calibrated prior to drilling and can subsequently be tracked by the stereo optical tracking cameras. Once the drill tip approaches the axis of an intended osteotomy, a "cross-hairs" view appears to guide the positioning, orientation and depth of the drilling (Fig. 4c). All the components of the prototype CAS system are mounted on a stand (Fig. 4d, 4e).

In the current experiment, the thermoplastic material was heated for 30 seconds in boiling water before being molded over the stone cast prior to the CT scan. The DICOM files from the CBCT were imported into the software and the planning of implant placements were done with the software planning module. The sections of the hardened thermoplastic shell where osteotomies were to be done were removed and the jaw tag was attached to the shell. The handpiece tag was securely attached to the hand piece with a clamp. The drilling axis was calibrated using a pin mounted on the jaw tag. Following insertion of the drill bit into the hand piece, a short drill tip calibration procedure was performed by touching a mark on the jaw tag. The position of the drill tip overlaid on the CT images could then be dynamically displayed and used to guide the drilling.

Osteotomies

Guided by the respective module of each of the five planning concepts, the osteotomies for the eight implants on each jaw were made on typodonts mounted in a mannequin (P-

6/5 TS, Frasaco GmbH, Tettnang, Germany) with silicone lining and accurate surgical anatomy under near clinical conditions. The experimental setup provided an approximate simulation of clinical conditions with typodonts that mimic human bone density, hardness and radiopacity. Ten typodonts were used, resulting in a total of 80 osteotomies with any of the five modalities, designated as one series of experiments. Three series were carried out by one clinician and one series each was undertaken by two additional clinicians. Consequently, 400 osteotomies was available for analysis for each of the five implant surgical transfer modalities, totaling altogether to 2000 osteotomies.

All osteotomies were done with surgical drills from Straumann (Straumann USA, Andover, USA), which were replaced in a regular pattern upon any signs of wear.

Assessment of accuracy

The 3D spatial orientation of the osteotomies in the test typodonts were compared to the same in the master typodont by the use of an optical tracking camera (MicronTracker model Hx40, Claron Technology Inc., Toronto, Canada). Special jigs were constructed with a mount for precise placement of the typodonts along with the inclusion of a calibration block. An L-frame with ø4 mm smooth steel cylinder affixed (Fig. 5a, Fig. 5b) was inserted in the calibration block and next successively in each osteotomy of the master. The software recorded the position and orientation of the steel cylinder at the entry point and at the apex of the tip. The same process was repeated for each of the five test typodonts. The following errors were evaluated by the accuracy evaluation software:

1. Error at the entry point of the implant, measured in mm
2. Error at the apex of the implant, measured in mm
3. Error in the orientation/direction of the actual osteotomy axis compared to planned osteotomy axis (or the angular error), expressed in degrees
4. Error in depth, measured in mm

Errors 1 and 2 are estimated by a 2D (x, y) Euclidean distance of the position vectors of the actual versus planned osteotomy. Error 3 or the angular error was estimated by taking the angle between the directional vectors of the actual versus planned osteotomy axis. Error 4 is the difference in the z-component of the position vectors. These provided a single coordinate system, to precisely overlay and compare measurements from both the master and test typodonts (Fig. 5c). Accuracy was then determined by comparing the measurements from the master typodont to all other typodonts. Fig. 6 illustrates the different inaccuracy calculations that were performed (entry error, apex error, vertical error, angular error and total error) in accordance with statistical results presented in current systematic reviews (Jung et al. 2009; Schneider et al. 2009; de Almeida et al. 2010; D'Haese et al. 2012; van Assche et al. 2012; Hultin et al. 2012).

After each accuracy assessment, the osteotomies were re-filled with proprietary cement (A-J OP UK K for mandible and A-J OP OK K for maxilla, Frasaco GmbH, Tettnang, Germany) with the same radiopacity as the Frasaco typodont jaw. The cement re-created a radiographically homogeneous mass without porosities, and a perceptible anisotropic sponginess upon drilling. The typodonts were then reused for evaluation of the next modality.

Statistical analysis

Deviation in total error, vertical error, horizontal error of the apex and entry position, as well as angular error, were measured and collected for each osteotomy across surgical planning modality and reported by mean, median and standard deviations. A marginal linear model using a generalized estimating equations (GEE) method was used to compare surgical methods, jaw types and models while accounting for the lack of independence in the outcome measurements. Omnibus Chi-square tests were used to determine if statistically significant differences across key factors could be identified. All analyses were undertaken by a statistician using SAS v9.2 (SAS, Cary, NC, USA).

Results

Eight osteotomies were made in five sets of maxillary and mandibular typodonts five times, 3 by one clinician and one each of two more, resulting in 400 sets of matched measurements across the five modalities. Power to detect statistical differences was based on the simple case of a paired t-test. Assuming a type I error rate of 5%, an arbitrary set within-cluster-correlation of 0.5, the 400 matched pairs of data provides 80% power to detect a small effect size (Cohen’s d = mean difference / SD) of 0.15. In the current data matrix an effect size of 0.15 translates to a difference in measurements of approximately 0.3 mm for total deviation, 0.18 mm for lateral deviation of entry and apex, as well as vertical deviation and 0.6 degrees for angle discrepancy.

Tables 1 and 2 are summaries of the different measurements. An overall difference in total apex deviation was found by surgical method (χ^2 = 17.71, p = 0.001). With an average deviation of 2.32, osteotomies drilled with a laboratory guide had significantly higher deviations compared to all other methods. The NobelGuide had the second highest average total apex deviation, which was significantly higher than for the Simplant SurgiGuide, Straumann Guided Surgery or the prototype dynamic CAS system. An overall difference in lateral apex deviation was found by surgical method (χ^2 = 26.50, p < 0.001). With an average deviation of 1.74, osteotomies drilled with a laboratory guide had significantly higher deviations compared to all other methods. An overall difference in vertical apex deviation was found by surgical method (χ^2 = 23.68, p < 0.001). With an average deviation of 0.73, osteotomies drilled with a laboratory guide had significantly lower deviations compared to all other methods. The NobelGuide had the highest average vertical apex deviation, which was significantly higher than for the Straumann Guided Surgery or the prototype dynamic CAS system.. An overall difference in lateral deviation of entry was found by surgical method (χ^2 = 21.63, p < 0.001). With an average deviation of 1.14, osteotomies drilled with a laboratory guide had significantly higher deviations compared to Simplant SurgiGuide, Straumann Guided Surgery and NobelGuide. The prototype dynamic CAS system had the second highest average lateral deviation of entry, which was significantly higher than for Straumann Guided Surgery or NobelGuide. An overall difference in angular deviation was found by surgical method (χ^2 = 30.85, p < 0.001). With an average deviation of 8.95, osteotomies drilled with a laboratory guide had significantly higher deviations compared to all other methods. The NobelGuide had the second highest average angular deviation of apex, which was significantly higher than for the Simplant SurgiGuide, Straumann Guided Surgery or the prototype dynamic CAS system.

Discussion

Our investigation was conducted as a pilot study to establish the applicability and accuracy of a novel dynamic CAS system in a simulated surgical environment. Hence, all osteotomies were made using ordinary surgical drills in a handpiece on silicon-covered typodonts mounted in a mannequin inside a clinic operatory.

The methodological setup to compare the 3D spatial orientation of the osteotomies in the test typodonts with the master typodont made use of the optical tracking camera, which is actually a component of the prototype dynamic CAS system. Interestingly, the exact same concept has recently been promoted as an optical impression method (Ono et al. 2013), with a reported reproduction accuracies within the 40-50 micron range.

The current study shows that the new dynamic CAS system is comparably as accurate to the existing static CAS systems when one considers the average values of the different modalities for surgical guidance. The lateral accuracy values are clinically acceptable, well within the 2 mm safety range that is suggested in most implant manufacturers' protocols.

When one considers the maximum errors measured, the range across the different guidance is spread wider, 2.92 (Simplant) to 4.95 mm (manual placement) at the entry and 3.92 (prototype dynamic) to 9.96 mm (manual placement) at the apex (Table 1), with the prototype dynamic CAS system showing the lowest maximum total apex error and the laboratory guide (manual) showing the highest. While the margin of apex position error associated with static guides is acceptable on average (less than 2mm), in practice there might be dangerous deviations in selected cases, meaning possible nerve damage, bleeding, and injury to the maxillary sinus, nasal cavity or adjacent teeth.

The observed mean values for axis deviation range from 2.99 (prototype dynamic) to 8.95 degrees (manual placement), but the outliers are surprisingly high across all modalities examined, from 11.94 (prototype dynamic) to 20.79 degrees (manual placement) (Table 2). Axis deviation may be of lesser importance for risk of damage to vital structures but under certain circumstances such as fitting of CAD-CAM presurgically fabricated prosthetic rehabilitation meant for immediate loading. Today, when there is a considerable effort to restore patients' dentitions in the shortest possible time with the least amount of post-surgical morbidity, flapless surgeries with immediate implant and prosthesis placement have become widely practiced. However, inaccuracies of this level can cause various complications if such procedures are followed, which might be due to inaccurate implant placement, as shown by the high variation of data or imprecise prosthesis fabrication (Jung et al. 2009; Schneider et al. 2009; de Almeida et al. 2010; D'Haese et al. 2012; van Assche et al. 2012; Hultin et al. 2012). Errors in accuracy in CAS are caused by several possible sources that likely add up or, less likely, compensate for each other. These deviations can result from errors in image processing, virtual planning, and technical fabrication of a surgical stent phase or during the actual surgery phase.

Image processing

During image acquisition, the brand of CBCT machine, its settings, the resulting voxel size and the field of view will all influence the accuracy (Schulze et al. 2011). CBCT measurements tend to underestimate the distances by approximately 1 mm on a full arch's length (Baumgaertel et al. 2009), and they very much depend on the unit used and the exposure settings (Hassan et al. 2010). Also, added inaccuracy could follow incorrect positioning of the radiographic template during image acquisition, especially with a decreasing number of remaining dentition (Russig & Schulze 2013). In the current study typodonts with only three teeth remaining in either jaw, which is close to being edentate, were used to simulate a compromising situation, resembling real life cases. Positioning of the radiographic templates was as accurate as possible for all tested modalities. The resulting DICOM files were processed with the individual software packages without any modifications. In the literature the mean error reported from image processing and segmentation was <0.5 mm, which also might need to be taken into account when analyzing results (Jung et al. 2009; Schneider et al. 2009; de Almeida et al. 2010; D'Haese et al. 2012; van Assche et al. 2012; Hultin et al. 2012).

Virtual planning

Throughout the virtual planning phase the greatest care was taken to follow the outlines of the osteotomies in the master typodont cast. Because of limited contrast resolution, precise outlining was occasionally difficult to achieve and in such cases the closest spacing was chosen symmetrically.

Technical fabrication of surgical stent

For dynamic CAS systems there is no need for a surgical guide in the traditional sense although a radiographic scanning guide needs to contain a radiopaque fiducial that subsequent optical fiducials can precisely relate to intra-orally. For static CAS systems however, fabrication of both radiographic and surgical guides becomes necessary. Ideally, such guides should be made out of a rigid material to avoid deformation and proper fitting for reproducibility of positioning. During fabrication of surgical guides an error range of 0.1-0.2 mm has been reported, which might be due to human error or material properties (Jung et al. 2009; Schneider et al. 2009; de Almeida et al. 2010; D'Haese et al. 2012; van Assche et al. 2012; Hultin et al. 2012). When it comes to stereolithographically produced static guides, the reported error range of fit is reported to vary 0.56-2.17 mm which is ascribed to planning and manufacturing errors, such as faulty ISO value setting in the planning software and different production protocols (Stumpel 2012). Moreover, different static CAS systems require different preparatory steps. In the current study stone casts were requested for manufacturing the Simplant *SurgiGuides* and these were retentive and very well fitting. Also the Straumann Guided Surgery guides, fabricated by a local laboratory demonstrated good fit. The *NobelGuide radiographic template* was constructed in the same laboratory and scanned with the double scanning procedure, as required by the manufacturer. However, when the *NobelGuide surgical templat*e was received directly from the manufacturing facility, it did not fit the typodont precisely and had to be slightly modified to achieve correct seating.

Surgical phase

The possible sources of error in the last part of the process, surgical application, are numerous. Correct seating of the guides is of utmost importance in any system, since a minor error can be amplified during drilling of the osteotomy at the apex level. With all the investigated methods the error at entry level was always less than at the apex level with the same system, which is supported by other studies (Jung et al. 2009; Schneider et al. 2009; de Almeida et al. 2010; D'Haese et al. 2012; van Assche et al. 2012; Hultin et al. 2012). The discrepancy probably depends on the amount of remaining teeth as well, the range of error in reduced residual dentition was shown to be 2-3 times as much as in a single tooth gap osteotomy (Behneke, et al. 2012). According to recent systematic reviews on accuracy, the mean deviation of entry was found to be 1.0 mm with static CAS guides on cadavers and models, which correspond to our data with the static CA- systems (0.76 (Simplant) - 0.9 mm (Straumann)). Moreover, the mean lateral error at the apex reported as 1.00-1.42 mm agreed to our data of 0.99 (Simplant) – 1.24 mm (Nobelguide), and the angular error as 4.7 degrees, which can be related to our finding of 3.09 (Simplant) - 4.24 degrees (Nobelguide) degrees.

For static CAS systems mechanical errors can also be caused by the incorrect angulation of the drills, since acrylic guides show a minor flexibility, with possible cracks and lost sleeves, especially if there is a Kennedy Class I or II situation (de Almeida et al. 2010). Restricted mouth opening can also interfere with instrument positioning, which is less of an influence during freehand drilling and dynamic CAS and in the anterior region of the arches (Neugebauer et al. 2010).

During osteotomies, human mistakes can be considerable with all methods, such as not utilizing the full length of the drill or not having the guide fully seated. It was therefore interesting to note in the current study that the most accurate vertical depths were achieved with freehand drilling under visual guidance (0.73 mm) compared to the other modalities (1.04-1.27 mm, Table 1). Another human variable is the surgeon’s dexterity – hand tremor and perception inaccuracies has been reported to cause deviations of up to 0.25 mm and 0.5 degrees in angulation (Ruppin et al. 2008). All three operators in the current study were right handed, which eliminated a bias based on left or right side inaccuracies in the osteotomies. In our dataset lateral deviation at entry was significantly higher with freehand osteotomy placement and the prototype dynamic CAS system. This was also true for the angular error, where the manual placement showed significantly higher deviation than any other modality (8.95 vs. 2.99-4.24 degrees, Table 2). These latter data is higher than that reported in the literature previously (Brief et al. 2005), but in contrast to that study the surgeons had no knowledge of the ‘ideal’, virtually planned implant position. Therefore there are personal differences as to where an ‘ideal’ position would be, which might result in diverse angulations. Also, a higher angular deviation observed with NobelGuide could be explained by the difference in guide fabrication, since it was made out of the thin acrylic and allowed for some flexibility of the guide. This material property might also explain the significantly higher horizontal error values of the osteotomies in the free-end position of the maxilla.

A decisive factor is also the surgeon's computer literacy, since there is a learning curve in all systems, especially with dynamic CAS systems. There is a significant paradigm shift, where the operator has to accept and get used to following the surgery on the monitor instead of by direct vision, as well as the eye-hand coordination has to be mastered to translate lateral and angle deviation information from the monitor to the patient. Another difference in thinking is the prompt for corrections during drilling when using dynamic CAS system. Since there is a live feedback about position and angulation of the drill, one tends to correct for eventual mistakes in position or angulation, which might lead to a funnel shaped osteotomy, possibly resulting in reduced primary stability.

Conclusion

A prototype dynamic CAS system has been implemented and tested and appear as accurate as three commercially available static CAS systems. CAS systems provided superior accuracy related to manual osteotomy placement, except vertically. There were discrepancies in accuracy between the upper and lower jaw, the upper jaw being less accurate in lateral deviations. All operators in this study exhibited an initial learning curve with the different CAS systems. The prototype dynamic CAS system appeared to be have the potential to become a useful tool for dental implant placement in the future. However, one has to keep in mind that there are multiple potential sources of error when applying CAS, some dependent on the operator, some not. Therefore one needs to use ample precaution and continuous self-assessment during all steps of the planning, transfer and surgical procedure to avoid possible iatrogenic results for the patient.

Acknowledgement

The authors acknowledge Drs. Brent Winnett, Waad Kheder and Romeo Paculanan for their contribution in the clinical component of the experiment.

J. Charles Victor, M.Sc., P.Stat. at the Toronto Institute for Clinical Evaluative Sciences provided the statistical analyses of the data.

This study was sponsored by Claron Technology Inc., Toronto, Canada through an research agreement with the University of Toronto Innovations and Partnerships Office.

References

Baumgaertel, S., Palomo, J. M., Palomo, L. & Hans, M. G. (2009) Reliability and accuracy of cone-beam computed tomography dental measurements. *American Journal of Orthodontics and Dentofacial Orthopedics* **136**: 19-25.

Behneke, A., Burwinkel, M., Knierim, K. & Behneke, N. (2012) Accuracy assessment of cone beam computed tomography-derived laboratory-based surgical templates on partially edentulous patients. *Clinical Oral Implants Research* **23**: 137-143.

Brief, J., Edinger, D., Hassfeld, S. & Eggers, G. (2005) Accuracy of image-guided implantology. *Clinical Oral Implants Research* **16**: 495-501.

D'Haese, J., Van De Velde, T., Komiyama, A., Hultin, M. & De Bruyn, H. (2012) Accuracy and complications using computer-designed stereolithographic surgical guides for oral rehabilitation by means of dental implants: A review of the literature. *Clinical Implant Dentistry and Related Research* **14**: 321-335.

de Almeida, E. O., Pellizzer, E. P., Goiatto, M. C., Margonar, R., Rocha, E. P., Freitas, A. C., Jr. & Anchieta, R. B. (2010) Computer-guided surgery in implantology: Review of basic concepts. *Journal of Craniofacial Surgery* **21**: 1917-1921.

Ewers, R., Schicho, K., Undt, G., Wanschitz, F., Truppe, M., Seemann, R. & Wagner, A. (2005) Basic research and 12 years of clinical experience in computer-assisted navigation technology: A review. *International Journal of Oral Maxillofacial Surgery* **34**: 1-8.

Fortin, T., Coudert, J.L., Champleboux, G., Sautot, P. & Lavallée S. (1995) Computer-assisted dental implant surgery using computed tomography. *Journal of Image Guided Surgery* **1**: 53-58.

Hassan, B., Couto Souza, P., Jacobs, R., de Azambuja Berti, S. & van der Stelt, P. (2010) Influence of scanning and reconstruction parameters on quality of three-dimensional surface models of the dental arches from cone beam computed tomography. *Clinical Oral Investigations* **14**: 303-310.

Hassfeld, S., Brief, J., Raczkowsky, J., Marmulla, R., Mende, U., & Ziegler, C. (2003) Computer-based approaches for maxillofacial interventions. *Minimally Invasive Therapy and Aliedl Technologies* **12**: 25-35.

Hultin, M., Svensson, K. G. & Trulsson, M. (2012) Clinical advantages of computer-guided implant placement: A systematic review. *Clinical Oral Implants Research* **23 Suppl 6**: 124-135.

Jung, R. E., Schneider, D., Ganeles, J., Wismeijer, D., Zwahlen, M., Hammerle, C. H. & Tahmaseb, A. (2009) Computer technology applications in surgical implant dentistry: A systematic review. *International Journal of Oral Maxillofacial Implants* **24 Suppl**: 92-109.

Miller, R. J. & Bier, J. (2006) Surgical navigation in oral implantology. *Implant Dentistry* **15**: 41-47.

Mischkowski, R. A., Zinser, M. J., Neugebauer, J., Kubler, A. C. & Zoller, J. E. (2006) Comparison of static and dynamic computer-assisted guidance methods in implantology. *International Journal of Computerized Dentistry* **9**: 23-35.

Neugebauer, J., Stachulla, G., Ritter, L., Dreiseidler, T., Mischkowski, R. A., Keeve, E. & Zoller, J. E. (2010) Computer-aided manufacturing technologies for guided implant placement. *Expert Review of Medical Devices* **7**: 113-129.

Ono, S., Yamaguchi, S., Kusumoto, N., Nakano, T., Sohmura, T. & Yatani, H. (2013) Optical impression method to measure three-dimensional position and orientation of dental implants using an optical tracker. *Clinical Oral Implants Research* **24**: 1117-1122.

Pjetursson, B. E., Bragger, U., Lang, N. P. & Zwahlen, M. (2007) Comparison of survival and complication rates of tooth-supported fixed dental prostheses (fdps) and implant-supported fdps and single crowns (scs). *Clinical Oral Implants Research* **18 Suppl 3**: 97-113.

Ruppin, J., Popovic, A., Strauss, M., Spuntrup, E., Steiner, A. & Stoll, C. (2008) Evaluation of the accuracy of three different computer-aided surgery systems in dental implantology: Optical tracking vs. Stereolithographic splint systems. *Clinical Oral Implants Research* **19**: 709-716.

Russig, L.L. & Schulze, R.K. (2013) Effects of minute misregistrations of prefabricated markers for image-guided dental implant surgery: an analytical evaluation. *Clinical Oral Implants Research* **24**: 1339-1346.

Sarment, D. P., Sukovic, P. & Clinthorne, N. (2003) Accuracy of implant placement with a stereolithographic surgical guide. *International Journal of Oral Maxillofacial Implants* **18**: 571-577.

Schneider, D., Marquardt, P., Zwahlen, M. & Jung, R. E. (2009) A systematic review on the accuracy and the clinical outcome of computer-guided template-based implant dentistry. *Clinical Oral Implants Research* **20 Suppl 4**: 73-86.

Schulze, R., Heil, U., Gross, D., Bruellmann, D.D., Dranischnikow, E., Schwanecke, U. & Schoemer, E. (2011) Artefacts in cbCT: a review. *Dentomaxillofacial Radiology* 40: 265-273.

Stumpel, L. J. (2013) Congruency of stereo lithographically produced surgical guide bases made from the same cbct file: A pilot study. *Clinical Implant Dentistry and Related Research* ***15**: 531-537*.

Van Assche, N., Vercruyssen, M., Coucke, W., Teughels, W., Jacobs, R. & Quirynen, M. (2012) Accuracy of computer-aided implant placement. *Clinical Oral Implants Research* **23** Suppl 6: 112-123.

Figure legends

Figure 1

(a) Master typodonts (Frasaco GmbH, Tettnang, Germany) highlighted with numbers to show sites of osetotomies, (b) Acrylic tooth set up on stone models duplicated from the master typodonts, (c) acrylic surgical guide placed on the stone models and (d) placed on the master typodonts.

Figure 2

CBCT images of master typodonts with osteotomies (a) maxilla, (b) mandible.

Figure 3

Surgical guides (maxilla, mandible). (a) Acrylic, laboratory made, (b) Simplant SurgiGuides (c) Straumann surgery templates and (d) NobelGuide surgical templates.

Figure 4

Characteristics of the prototype dynamic CAS system. (a) the reference tag for the jaw with the black and white optical fiducials, (b) the reference tag for the handpiece with the black and white optical fiducials, (c) user interface of the prototype software. The left panel contains the menu options, and the visual feedback portion, as well as information on the calibrated drill tip diameter. Top middle is a panoramic overview, top right is the field of view of the camera. The sections in the bottom are the guiding cross hairs and visual representation of the planned implant position and its relation to the drill in real time, (d) experimental setup from the clinician's perspective and (e) overview of the experimental setup.

Figure 5

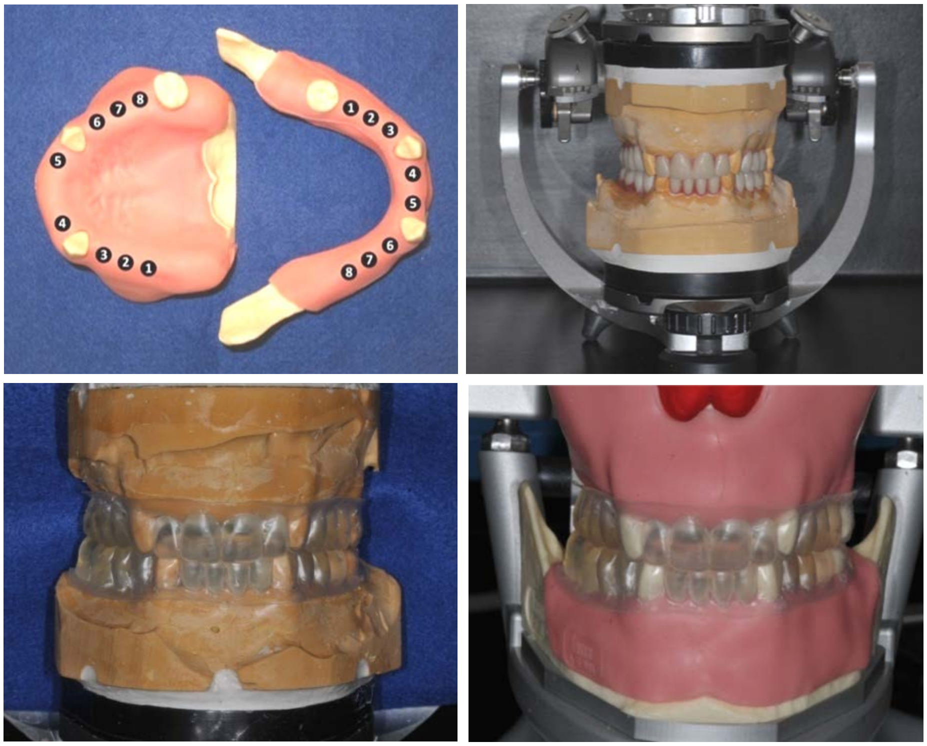
Accuracy estimation assembly. (a) calibration and positioning jigs with measuring probe, (b) positioning jigs with master typodonts in place and (c) user interface of accuracy measurement software.

Figure 6

Accuracy measurements. Figure adopted from Brief et al. (2005) Blue – ideal position of dental implant, green – position to compare to ideal position. (A) error at entry, (B) error at apex, (C) vertical error, (D) angular error, (E) total error.

Figure 1.

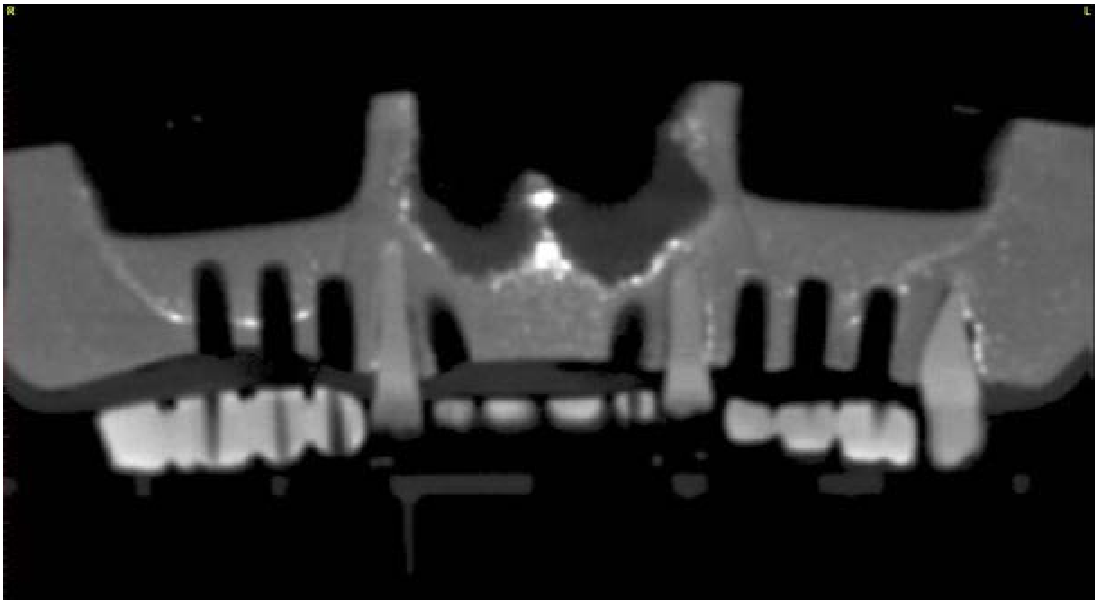
a b



c d

Figure 2

a



b

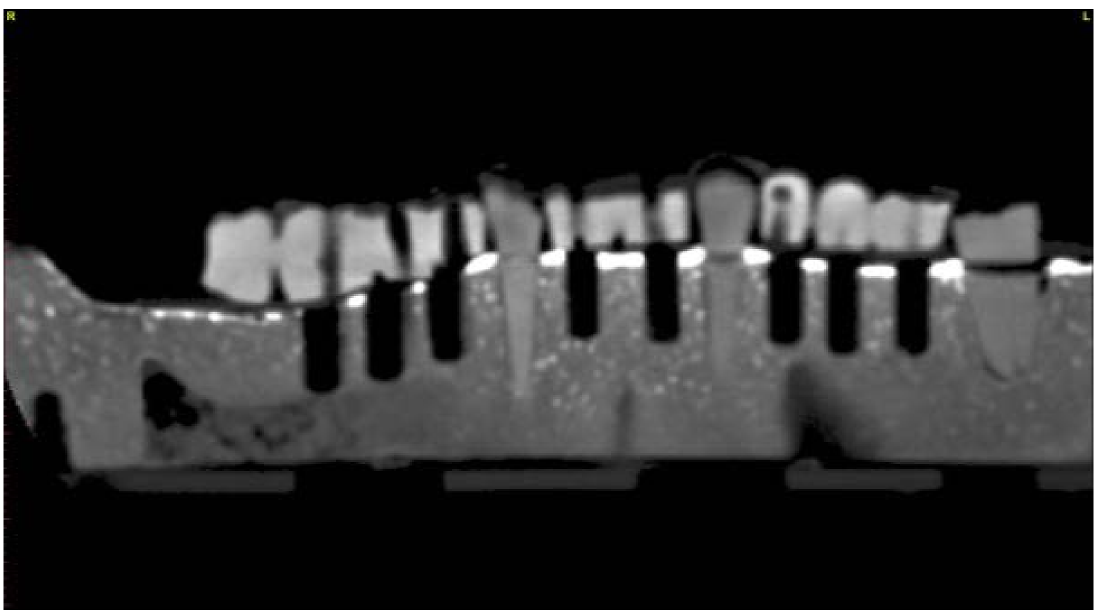


Figure 3

a

b

c

d

Figure 4

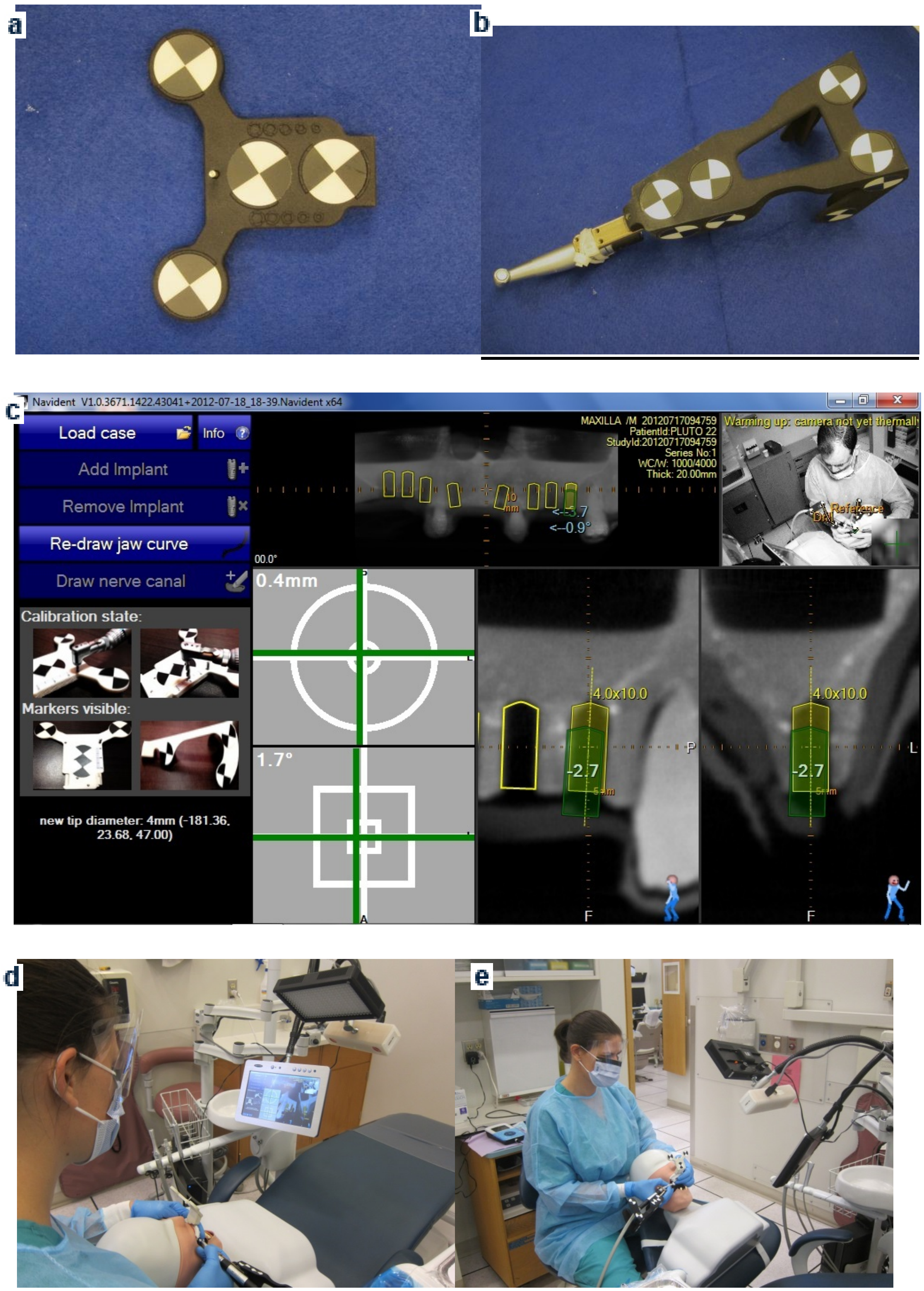

a
b
c
Navident V1.0.3671.1422.43041+2012-07-18_18-39.Navident x64
Load case
Info
Add Implant
Remove Implant
Re-draw jaw curve
Draw nerve canal
Calibration state:
Markers visible:
new tip diameter: 4mm (-181.36, 23.68, 47.00)
MAXILLA /M 20120717094759
PatientId:PLUTO 22
StudyId:20120717094759
Series No:1
WC/W: 1000/4000
Thick: 20.00mm
Warning up: camera not yet thermally
Reference
00.0°
0.4mm
1.7°
4.0x10.0
-2.7
P
L
F
A
d
e

Figure 5

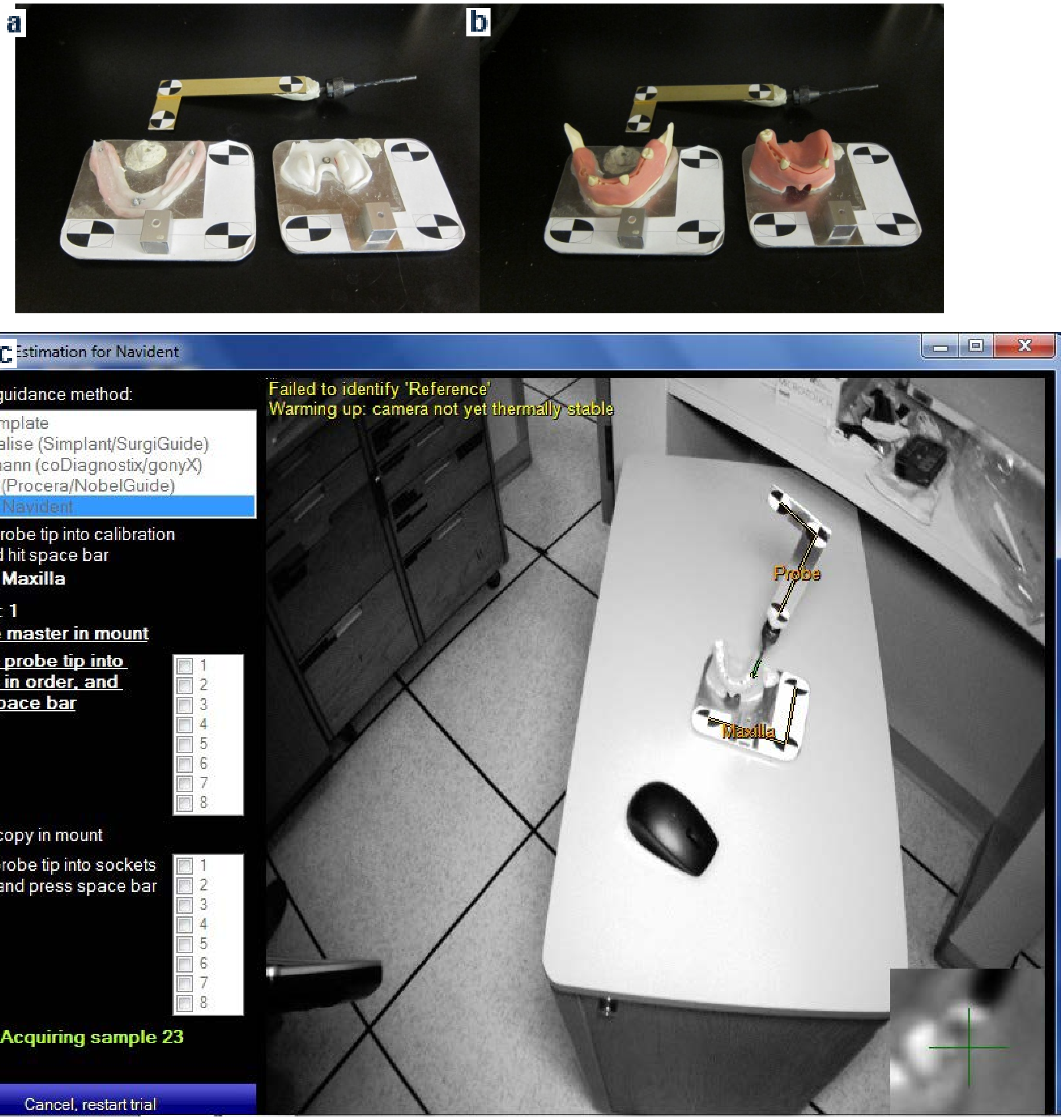
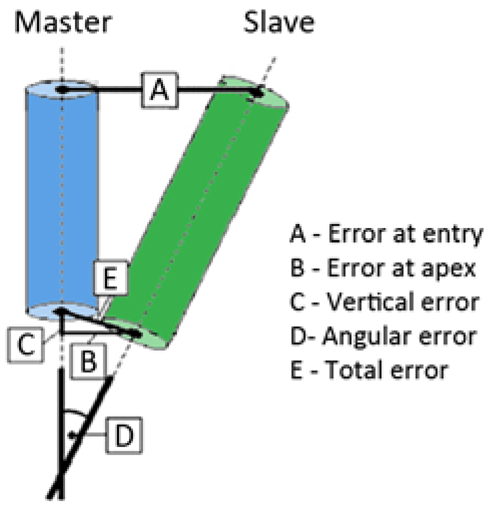

a
b
c
Accura
Estimation for Navident
1. Select guidance method:
A. Lab template
B. Materialise (Simplant/SurgiGuide)
C. Straumann (coDiagnostix/gonyX)
D. Nobel (Procera/NobelGuide)
E. Claron Navident
2. Insert probe tip into calibration block and hit space bar
Jaw: Maxilla
Trial: 1
3. Place master in mount
4. Insert probe tip into sockets in order, and press space bar
1 2 3 4 5 6 7 8
5. Place copy in mount
6. Insert probe tip into sockets in order, and press space bar
1 2 3 4 5 6 7 8
Acquiring sample 23
Cancel, restart trial
Failed to identify 'Reference'
Warming up: camera not yet thermally stable
Probe
Maxilla

Figure 6


Master
Slave
A
E
C
B
D
A - Error at entry
B - Error at apex
C - Vertical error
D- Angular error
E - Total error

Tables

Table 1. Deviations of the pilot borehole position in the test models compared to the master model (all data: mean ± SD, Median, (min-max) (mm)). Each cell in the table represents 400 osteotomies.

	Laboratory guide	Straumann Guided Surgery	Simplant SurgiGuide	NobelGuide	Prototype dynamic CAS system
Lateral error entry	1.14 ± 0.68 1.0 (0.02-4.95)	0.9 ± 0.48 0.9 (0.05-4.66)	0.76 ± 0.54 0.7 (0.02-2.92)	0.81 ± 0.55 0.7 (0.05-4.31)	1.14 ± 0.55 1.1 (0.04-3.64)
Lateral error apex	1.74 ± 1.07 1.5 (0.04-5.95)	1.19 ± 0.62 1.1 (0.09-4.78)	0.99 ± 0.64 0.9 (0.07-3.36)	1.24 ± 0.8 1.1 (0.02-5.99)	1.18 ± 0.56 1.1 (0.05-3.19)
Vertical error apex	0.73 ± 0.71 0.6 (0.00-3.40)	1.05 ± 0.86 0.6 (0.00-4.81)	1.1 ± 0.79 1.0 (0.00-2.98)	1.27 ± 0.86 1.2 (0.00-4.06)	1.04 ± 0.71 0.8 (0.00-3.34)
Total error apex	2.32 ± 1.18 1.9 (0.14-9.96)	1.71 ± 0.86 1.6 (0.23-5.05)	1.46 ± 0.76 1.4 (0.10-4.99)	1.91 ± 0.94 1.6 (0.06-6.23)	1.71 ± 0.61 1.6 (0.22-3.92)

Table 2. Angular deviation of the axis of the osteotomies in the test models compared to the axis of the osteotomies in the master typodont models (all data: mean ± SD, Median, (min-max) (degrees)). Each cell in the table represents 400 osteotomies.

	Laboratory guide	Straumann Guided Surgery	Simplant SurgiGuide	NobelGuide	Prototype dynamic CAS system
Axis deviation	8.95 ± 4.65 8.7 (0.33-20.79)	3.31 ± 1.86 3.3 (0.20-12.52)	3.09 ± 1.9 3.0 (0.16-14.58)	4.24 ± 2.66 3.8 (0.09-17.05)	2.99 ± 1.68 2.8 (0.14-11.94)