DR. ALI AL-RIMAWI (Orcid ID : 0000-0001-5258-3891)

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Trueness of cone-beam computed tomography versus intra-oral scanner derived three dimensional digital models: An e*x-vivo* study.

Ali Al-Rimawi[1,2], Eman Shaheen[1], Emad A. Albdour[1,2], Sohaib Shujaat[1], Constantinus Politis[1], Reinhilde Jacobs[1,3]

[1] OMFS IMPATH research group, Department of Imaging and Pathology, Faculty of Medicine, University of Leuven and Oral & Maxillofacial Surgery, University Hospitals Leuven, Leuven, Belgium

[2] Department of dentistry, Royal Medical Services, Jordanian Armed Forces, Jordan

[3] Department of Dental Medicine, Karolinska Institutet, Huddinge, Sweden

CBCT versus intra-oral scanner derived 3D digital models

Corresponding author:

Sohaib Shujaat
Sohaib.shujaat@student.kuleuven.be
+32 488065857
Campus Sint-Rafaël | Kapucijnenvoer 33| 3000 Leuven |Belgium

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Keywords: Digital models, Trueness, implantology.

Abstract:

Objectives:

To compare the trueness of 3D digital models derived from CBCT and IOS and to evaluate their accuracy for implementation in oral implant rehabilitation.

Materials and methods:

A dry human mandible with a full set of intact teeth was included in the study. The mandible was scanned using Trios IOS and 4 different CBCT machines with various protocols for generation of 3D digital models. A μCT was utilized to scan each tooth individually. Following registration and segmentation, the trueness evaluation of 3D digital models was carried out by part comparison analysis and color-coded mapping of the superimposed teeth surfaces.

Results: The 4 CBCT-derived 3D digital models with different protocols had better trueness than Trios IOS. Newtom VGi evo (110 KV), ProMax 3D (90 kV), 3D Accuitomo 170 (90 kV) , Green 21 (110kV) and Green 21 (90 kV) showed significantly better trueness than IOS. Whereas, 3D Accuitomo 170 and ProMax 3D CBCT devices with 70kV protocol showed better trueness without any significant difference with IOS.

Conclusion: CBCT-derived 3D digital models showed better trueness when compared with IOS. When CBCT data is available for preoperative planning for oral implant rehabilitation, it may preclude the need for IOS for obtaining 3D study models

Introduction

The field of dental implantology is continuously evolving with the growth in technological advances. One of this evolution has been the application of digital work flow for the purpose of diagnosis and treatment planning in implantology, such as; application of three dimensional (3D) imaging systems, 3D planning softwares, Cone Beam Computed Tomography (CBCT) and intra-oral scanners (IOS)(Jung et al., 2009; Tahmaseb, Wismeijer, Coucke, & Derksen, 2014).

Digital 3D models have become an essential component of the work flow for implant rehabilitation (Arcuri et al., 2015; Dolcini, Colombo, & Mangano, 2016), which can be acquired either by a direct or an indirect method. Direct approach includes application of IOS or CBCT imaging, if diagnostically justified. Indirect methods involve scanning of plaster cast or conventional impressions with an optical laser scanner or CBCT (Fasbinder, 2013; Güth, Keul, Stimmelmayr, Beuer, & Edelhoff, 2013).

As with any new technology, accuracy testing is an essential requirement. Accuracy is an expression of trueness and precision. Trueness represents the closeness of the measurement to the accepted reference value, whereas, precision represents the closeness of repeated measurement of the same object (Standardization, 1994) . According to the available evidence, accuracy of IOS-derived digital models is clinically acceptable and comparable to that of conventional models (Albdour et al., 2018; Hack, 2015; Nedelcu, Olsson, Nyström, Rydén, & Thor, 2018; Rossini, Parrini, Castroflorio, Deregibus, & Debernardi, 2016). The trueness of an IOS can be assessed by registering the 3D images on a reference model obtained by a high resolution industrial optical scanner, articulated arm, coordinate measuring machine or micro computed tomography (μCT) (Ahlholm, Sipilä, Vallittu, Jakonen, & Kotiranta, 2018; Aragón, Pontes, Bichara, Flores-Mir, & Normando, 2016;

Chochlidakis et al., 2016; Goracci, Franchi, Vichi, & Ferrari, 2016; Imburgia et al., 2017; Yang, Lv, Liu, Si, & Feng, 2015). At the same instance, the accuracy of CBCT images has been confirmed utilizing various devices (Baumgaertel, Palomo, Palomo, & Hans, 2009; Lascala, Panella, & Marques, 2004), however the accuracy of CBCT-derived digital models has not yet been assessed adequately (Engelbrecht, Fourie, Damstra, Gerrits, & Ren, 2013). Literature suggests two methods for assessing the accuracy of CBCT-derived digital models. The first method relies on linear, physical and radiographical measurements for assessing the accuracy of 3D digital models(Al Ali 2017). The second method involves using µCT-derived 3D reconstruction of teeth as a reference to evaluate the accuracy of digital models. Both methods showed that CBCT-derived digital models were found to be accurate and clinically acceptable for dental arch analysis (Al-Rawi, Hassan, Vandenberge, & Jacobs, 2010; Maret et al., 2012).

No studies were found comparing the trueness of CBCT- derived digital 3D models to the corresponding IOS derived ones, having µCT as a gold standard and IOS as a clinical reference standard. Therefore, the aim of this study was to compare the trueness of 3D digital models derived from CBCT and IOS for implementation in digital work flow of oral implant rehabilitation.

Materials and methods:

A dry human mandible with a full set of teeth was included in the study which was approved by the Ethical Review Board of the University Hospitals Leuven (ML9535/ML9248, ERB University Hospitals Leuven). The mandible was covered with a soft tissue substitute (Mix D) (Figure1), used for simulation had similar x-ray scattering and absorption properties to that of normal human soft tissue(Dea, 1948; Dea & HC, 1949) . For minimizing the influence of operator experience on intra-oral scanning results, the prepared mandibular model was scanned by an investigator experienced in digital dentistry and intra-oral scanning (E.B.). Following calibration of IOS (Trios® 3, 3Shape, Copenhagen, Denmark) based on manufacturer's guidelines, scanning was performed in a well illuminated dental office and the room temperature was maintained at 21°C. A full arch scan was performed by a single continuous arc movement starting from occlusal surface of mandibular left 2nd molar to right 2nd molar with slow wiggling motion in the anterior buccolingual area. Thereafter, the scanner tip was rolled at 45° to 90° to the lingual and buccal side for scanning the lingual and buccal surfaces from one side to another. During the scanning process, all captured areas were continuously visualized on a screen to ensure proper scanning of the full arch without any missing surfaces. This resulted in formation of a digital impression model which was then exported as a stereolithographic (STL) file using OrthoAnalyzer software (Figure 2). At the same instance, four CBCT devices (3D Accuitomo 170, Newtom VGi evo, ProMax 3D, Green 21) with different protocols (Table 1) were used to acquire seven 3D reconstructions of the dry mandible in the Digital Imaging and Communications in Medicine (DICOM) format. All CBCT scans were performed by an experienced dentomaxillofacial radiologist.

Following creation of 3D digital models from IOS and CBCT, teeth were extracted from the jaw and scanned one by one with a μCT device (SkyScan 1172, Aartselaar, Belgium). The scanning parameters included 100 kilovolt (kV), 100 μA, Aluminum filter 0.5 mm, rotation step 0.7 ° (360 ° rotation) and 12.8 μm image pixel size. The cross-section slices were reconstructed by utilizing SkyScan's volumetric reconstruction software (NRecon) with a beam hardening correction of 60% and ring artifact correction of 5. Reconstructed slices were saved in the DICOM format.

Trueness evaluation protocol

Image registration

The DICOM images of the CBCT scans and DICOM images of the µCT were imported into Amira 6.3 (FEI, Hillsboro,USA) software. All CBCT and µCT scans were superimposed in one 3D space via voxel-based registration with mutual information(Collignon, 1995; Pluim, 2003; Viola, 1995) (Figure 3). The IOS scanned mandible was registered to the other scans using surface-based registration in Proplan software (version 3.0, Materialise, Leuven, Belgium).

Segmentation

All registered CBCT and µCT 3D images were segmented with the application of thresholding technique in Amira software Version 6.3 (FEI, Hillsboro, USA). Thereafter, data was exported as STL file format.

Trueness evaluation

The STL files of registered scans (CBCT, µCT, Trios IOS) were imported into 3-matic medical software (version 12.0, Materialise, Leuven, Belgium). All superimposed scans were trimmed using the same plane to isolate each tooth individually. To evaluate the trueness, the distance maps (Euclidean distance) between surfaces were calculated by applying part comparison analysis with color coded map for acquiring the root mean square (RMS) error (Figure 4). This analysis was performed between µCT scan and other scans for every single tooth taking the µCT, the gold standard, as reference.

Statistical analysis

Statistical analysis was conducted in MedCalc software version 16.4® (Oostende, Belgium). Mean, standard deviation (SD), median and interquartile range (IQR) of RMS error were calculated for all the data. Wilcoxon paired test was applied to compare RMS between IOS derived digital model and models generated from each CBCT protocol. Level of significance was set at $P < 0.05$.

Results

Table 2 shows the mean, SD, median and IQR of RMS for IOS and CBCT derived digital models compared to µCT. Overall, IOS showed the highest mean discrepancy (120 ± 34 µm), whereas, Newtom VGi evo (110 kV) showed the lowest discrepancy (82 ±23µm) when compared with µCT. Out of all the CBCT devices and protocols, ProMax 3D (70 Kv) observed the highest mean discrepancy (113 ±19µm). Figure 5 shows a boxplot for the trueness deviation of the IOS and CBCT derived digital models.

Table 3 highlights the trueness of CBCT-derived digital models compared to IOS as a clinical reference standard. All CBCT-derived models had a significantly better trueness when compared to Trios IOS, except 3D Accuitomo 170 (70 kV) and ProMax 3D (70 kV) which showed improved trueness, but no significant difference was observed.

Discussion

This *ex-vivo* study was performed to compare the trueness of CBCT-derived digital models with IOS as the clinical reference and µCT as a gold standard. µCT has been proven to be useful tool for qualitative and quantitative analysis of teeth, bone and implants (Swain & Xue, 2009). In addition, it provides a basis for precise and accurate assessment of internal dental structural parameters in three dimensions (Olejniczak, Tafforeau, Smith, Temming, & Hublin, 2007; Peters, Laib, Rüegsegger, & Barbakow, 2000) .

In the following study, 3D models acquired by µCT with isotropic voxel size of 12.8 µm, were used as a golden reference to evaluate the trueness of CBCT and IOS derived 3D digital models. The results showed that all CBCT-derived 3D digital models had better trueness than IOS. The mean discrepancy for all CBCT scans ranged from 82µm (Newtom VGi evo 110 kV) to 113µm (ProMax 3D 70kV), and for the IOS it was 120 µm. CBCT scans with higher kV settings had better trueness value compared to lower kVs, which might be due to the fact that the higher kV provides better image quality(Pauwels et al., 2014).

Various studies evaluated the trueness of IOS and it ranged between 58 µm to 80 µm (Ender & Mehl, 2013; Gan, Xiong, & Jiao, 2016; Renne et al., 2017). These findings were inconsistent with the trueness value of 120 µm suggested by our study, which could have resulted as the whole dental arch was scanned which is associated with more degree of error compared to scanning of smaller region (Rhee, Huh, Cho, & Park, 2015). Another limiting aspect was the study's ex-vivo design and inability to replicate the oral environmental factors such as, intra-oral temperature, oral humidity and illumination (Arakida, Kanazawa, Iwaki, Suzuki, & Minakuchi, 2018; Park, Lim, Yi, Han, & Lee, 2018). Furthermore, the present study design was limited to a dry mandible without any restorations, whereas, patients requiring dental implant may present with restorations, potentially creating artefacts in the CBCT scanning , particularly at the occlusal level. In such scenario the digital scan may be registered as an accurate occlusal key on top of the anatomical CBCT dataset, allowing for integrated planning. (Jacobs, Salmon, Codari, Hassan, & Bornstein, 2018) . However, unlike aforementioned studies, a different protocol was established involving voxel-based superimposition of 3D models and utilization of micro-CT as a gold standard for evaluating accuracy. Evidence suggests various methodologies for observing the trueness of IOS, therefore, it is recommended to establish a universal protocol for scanning and assessing accuracy.

Our finding related to the mean discrepancy of IOS was in accordance with a recent in-vivo study which also evaluated the trueness of Trios IOS (Albdour et al., 2018). In the following study, CBCT-derived models had improved trueness but both CBCT and IOS devices have certain pros and cons. CBCT has higher accuracy compared to IOS but it comes with the limitation of radiation exposure and presence of metal and motion artefacts which can affect the quality and accuracy of the 3D digital models(Codari, de Faria Vasconcelos, Ferreira Pinheiro Nicolielo, Haiter Neto, & Jacobs, 2017). Similarly, IOS has the advantage of scanning without radiation exposure to patient and provides better 3D reconstruction of soft tissue (Barone, Paoli, & Razionale, 2013), at the same instance, in a clinical setting the accuracy of IOS may be affected by the presence of blood, saliva, light reflection and patient motion (Hack, 2015). Additionally, scanning of dental occlusion is another main limitation associated with IOS, therefore, it is necessary to improve the accuracy of IOS for inter-occlusal registration (Wong, Esguerra, Chia, Tan, & Tan, 2018).

The trueness value of the digital models, whether obtained by CBCT or IOS, is still insufficient for precise crown and bridge work without occlusal discrepancies , which requires a trueness value of around 20µm (Hamalian, Nasr, & Chidiac, 2011; Jacobs & van Steenberghe, 1994).

Conclusion

CBCT-derived 3D digital models showed better trueness when compared with IOS. When CBCT data is available for preoperative planning for oral implant rehabilitation, it may preclude the need to obtain IOS-derived models. However, CBCT's failure to provide sufficient information related to mucosal support and reduced accuracy in presence of metal artefacts can negatively influence the surgical guide design, thereby, in such situations CBCT and IOS image fusion should be considered. Further investigations are required to study the accuracy of IOS and CBCT in partial and complete edentulous ridges with implants.

Acknowledgements

Conflict of interests

None to declare

Author contributions

A.R., E.S., E.B., S.S., R.J., and C.P. involved in concept/design. A.R and E.A. performed data acquisition. A.R., E.B., S.S. contributed to statistics. A.R., E.S., E.B., S.S. involved in data analysis/interpretation. A.R., E.S., E.B., S.S. drafted the manuscript. E.B., S.S., R.J. and C.P. involved in critical revision of the article. R.J. and C.P. performed final approval of the article. A.R., E.S., E.B., S.S., R.J. and C.P. agreed to be accountable for all aspects of the work.

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Table 1. Technical data of CBCT devices used for 3D model making

CBCT machine	Company	Tube voltage (Kv)	Tube Current (mA)	Voxel size (µm)	Field of view (mm)
3D Accuitomo 170	Morita, Kyoto, Japan	70	8	160	80×80
3D Accuitomo 170	Morita, Kyoto, Japan	90	5	160	80×80
ProMax 3D	Planmeca Oy, Helsinki, Finland	70	8	150	80×80
ProMax 3D	Planmeca Oy, Helsinki, Finland	90	5	150	80×80
Newtom VGi evo	QR, Verona, Italy	110	3	150	80×80
Green 21	Vatech , Hwaseong, Korea	90	5	120	80×80
Green 21	Vatech , Hwaseong , Korea	110	4	120	80×80

Table 2. Showing the mean, standard deviation, Median and Inter quartile range of RMS values of CBCT derived and digital impression derived 3D models representing the discrepancy from the reference micro CT the gold standard

Device	Mean (µm)	Standard deviation (µm)	Median (µm)	Inter quartile range
Trios scanner	**120**	**34**	**125**	**50**
3D Accuitomo 170 (70 kV)	**103**	**26**	**102**	**34**
3D Accuitomo 170 (90kV)	**86**	**27**	**83**	**32**
Newtom VGi evo (110 KV)	**82**	**23**	**80**	**24**
ProMax 3D (90 kV)	**86**	**25**	**86**	**9**
ProMax 3D (70 kV)	**113**	**19**	**109**	**14**
Green 21 (90 KV)	**96**	**22**	**86**	**12**
Green 21 (110 KV)	**88**	**21**	**89**	**27**

Table 3. Significance test (Wilxocon test) of the RMS of each CBCT protocol compared to IOS scanner

CBCT scanning Protocol		P value
3D Accuitomo 170	(70 kV)	0.1602
3D Accuitomo 170	(90kV)	0.0137*
Newtom VGi evo	(110kV)	0.002*
ProMax 3D	(90 kV)	0.0098*
ProMax 3D	(70 kV)	0.375
Green 21	(90kV)	0.0273*
Green 21	(110kV)	0.0195*

***indicates statistical significance (P<0.05)**

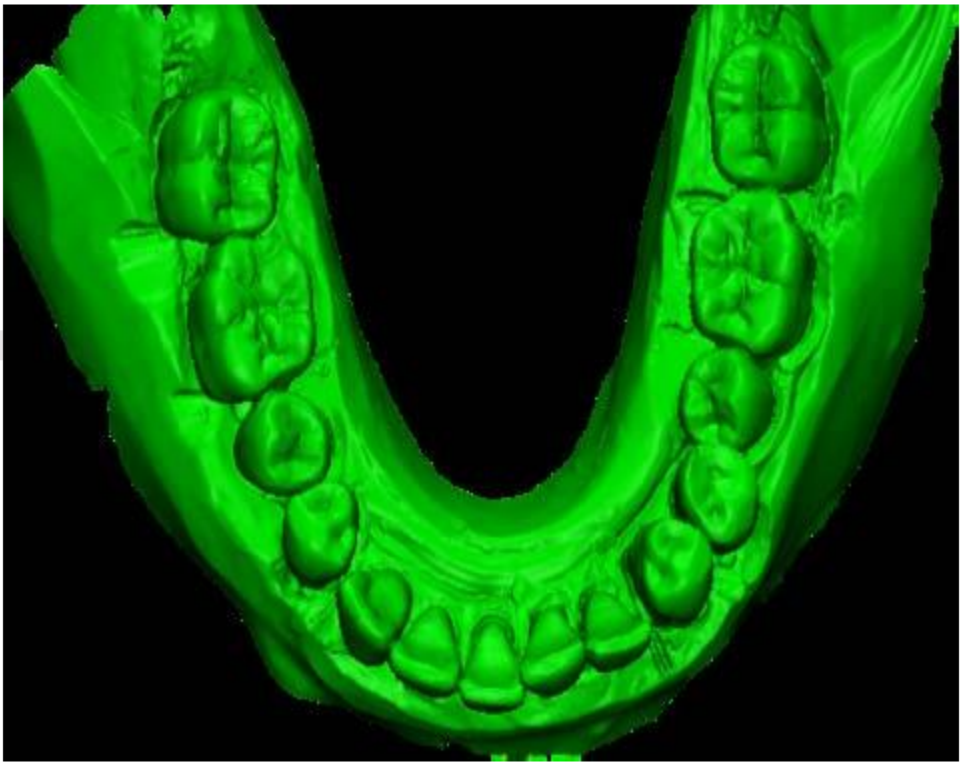
Figure 1. Human mandible with full dentition covered with Mix D material

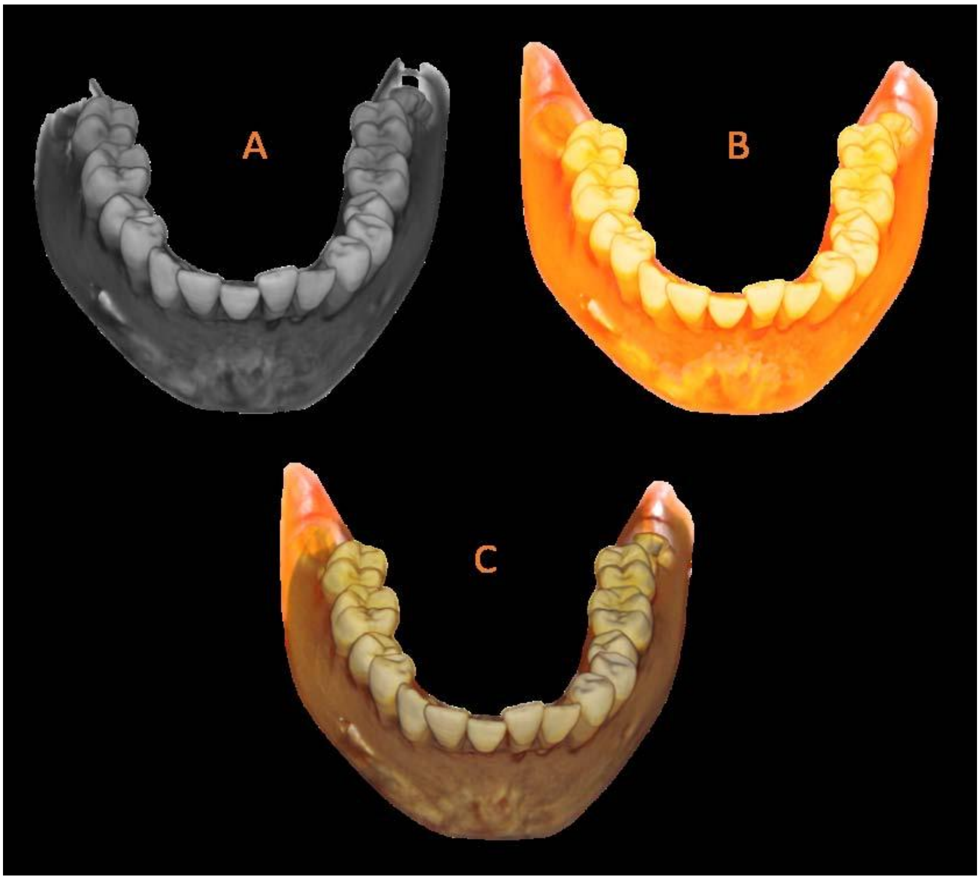
Figure 2. Human mandible digital model captured by Trios intal oral scanner

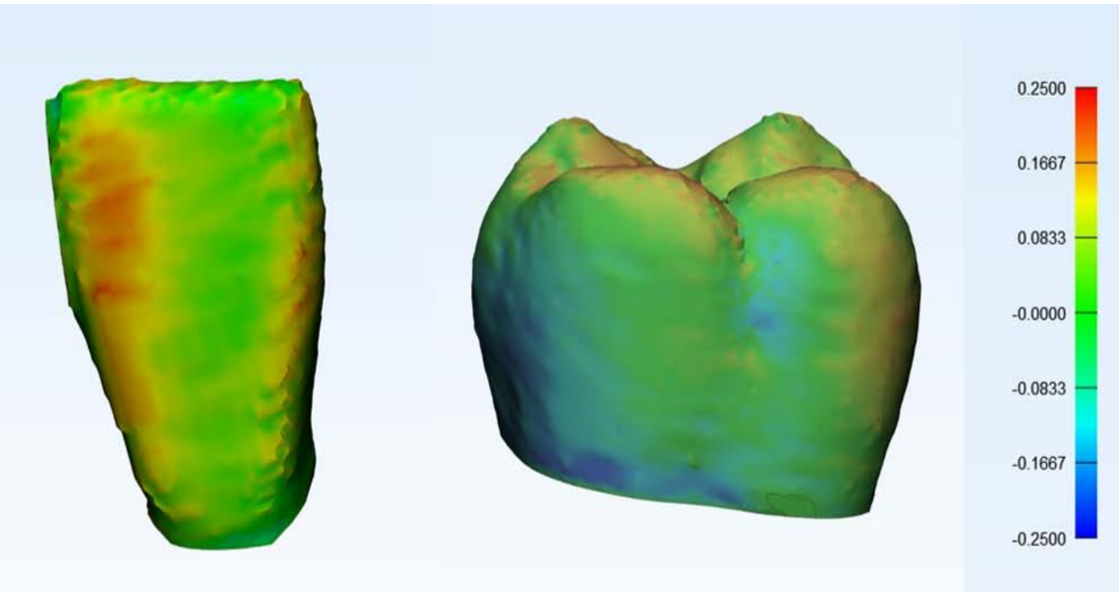
Figure 3A, 3B. Two different CBCT digital model scans, **3C.** The two models Registered in one 3D space

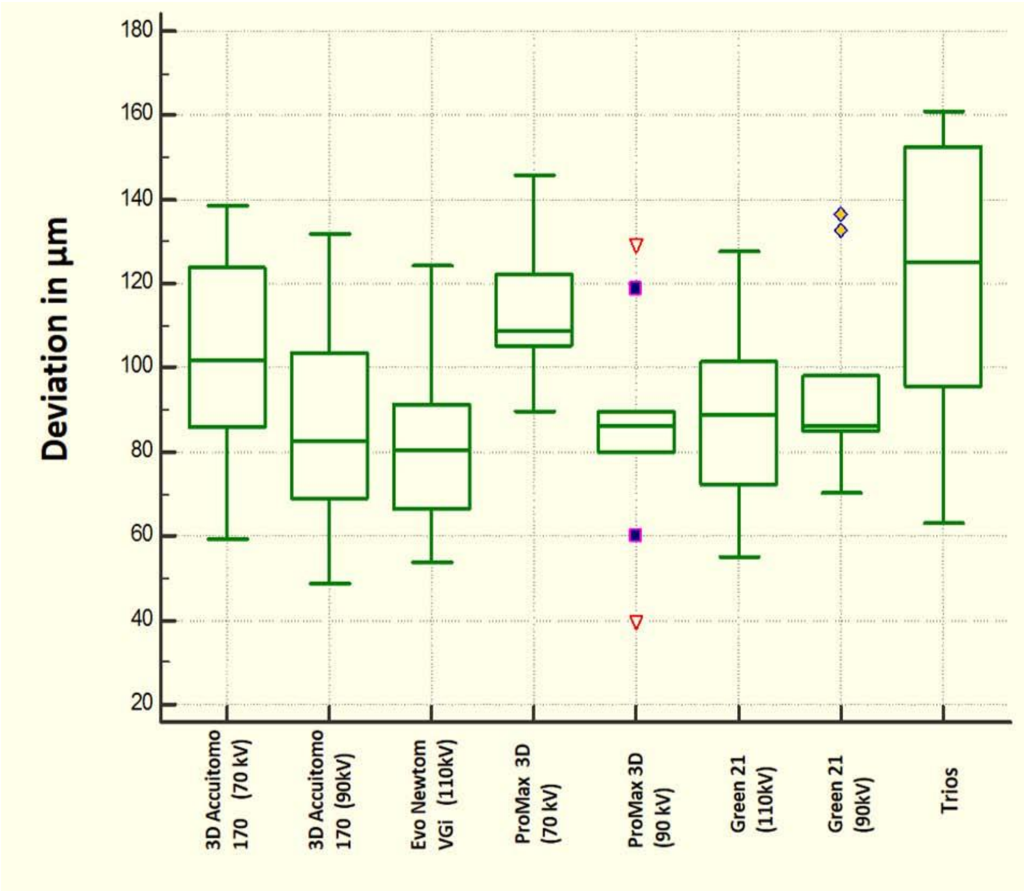
Figure 4. Color deviation map and surface comparison analysis in two samples 4A. incisor 4B. molar. Blue areas represent negative discrepancy (3D model is smaller than the reference), and the red areas represents positive discrepancies (3D model is larger than the reference).

Figure 5. Box plot of trueness deviation for the different CBCT scans and Trios IOS scan based on RMS values. The line within the box represents the median.




A
B
C


0.2500
0.1667
0.0833
-0.0000
-0.0833
-0.1667
-0.2500


Deviation in µm
180
160
140
120
100
80
60
40
20
3D Accuitomo 170 (70 kV)
3D Accuitomo 170 (90kV)
Evo Newtom VGi (110kV)
ProMax 3D (70 kV)
ProMax 3D (90 kV)
Green 21 (110kV)
Green 21 (90kV)
Trios