Dental Materials

New method to analyze resolution acquisition for Intraoral scanners

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Abstract:	- In dentistry, 3D intraoral scanners (IOSs) are gaining increasing popularity for the production of dental prostheses. However, the quality of an IOS in terms of resolution remains a determining factor of choice for the practitioner; a high resolution is a quality parameter that can reduce error in the production chain. To the best of our knowledge, the evaluation of IOS resolution is not clearly established in the literature. This study provides a simple assessment of the resolution of an IOS by measuring a reference sample and highlights various factors that may influence the resolution. A ceramic tip was polished to create a very thin object with an edge size less than the current resolution stated by the company. The sample was scanned by micro-computed tomography (micro CT) and an IOS, and the resulting meshes were compared. In the mesh obtained with the IOS, the distance between two plans on the edge was approximately 100 micrometers, and that obtained with micro tomography was 25 micrometers. The curvature values were 27.46 (SD 14.71) µm-1 and 5.18 (SD 1.16) µm-1 for micro-CT and IOS, respectively. These results show a clear loss of information for objects that are less than 100 µm. As there is no normalized procedure to evaluate the resolution of intraoral scanners, the method that we developed could be a positive parameter for the control of IOS performance by practitioners.

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To Editor in Chief, Dental Material

Montpellier, November 22 2019

Dear Editor in Chief,

Please find enclosed for re-submission, article now titled: "New method to determine intra-oral scanner resolution", by Alban Desoutter, Gérard Subsol, Eric Fargier, Alexandre Sorgius, Hervé Tassery, Michel Fages, Frédéric Cuisinier.

Authors confirm that this manuscript has not published elsewhere and is not under consideration by another journal. The corresponding author has no interest of conflict for any particular party to declare (conflict of interest none).
We declare that the images in the manuscript are original, tables made by the authors themselves. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

We have modified our work to take into account reviewers comments, and suggestion of bibliography references.

We want, by the present letter, clarify two points:
-The reproducibility of tested object conception is not important at this step of our study. We focus on reproducibility of method. Indeed, most important thing is the dimension of the top of the tip, to be sur that the size of detail is under the minimal resolution announce by the companies. Such a structure is quite simple to obtain in a laboratory equipped with polishing table, disks and diamond pastes, as described in material & method. This fact explains the participation of LNE, to evaluate the dimension of the edge of the tip. Angulation is 40.8 degrees. But the suggestion of industrially manufactured ceramic gauge block is pertinent to create a reproducible sample for the commercialization.

-Photos taken with LNE measuring machine, were intended for confirm the order of magnitude of the object size in the region of interest. For this task, a 2D image with a high resolution is enough to have this information with a high level of certitude. The diameter of the circle fitted with curvature of the tip is around 15 micrometers.

Sincerely yours,

Alban Desoutter.

New method to analyze resolution acquisition for Intraoral scanners

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Abstract - In dentistry, 3D intraoral scanners (IOSs) are gaining increasing popularity for the production of dental prostheses. However, the quality of an IOS in terms of resolution remains a determining factor of choice for the practitioner; a high resolution is a quality parameter that can reduce error in the production chain. To the best of our knowledge, the evaluation of IOS resolution is not clearly established in the literature. This study provides a simple assessment of the resolution of an IOS by measuring a reference sample and highlights various factors that may influence the resolution.

A ceramic tip was polished to create a very thin object with an edge size less than the current resolution stated by the company. The sample was scanned by micro-computed tomography (micro CT) and an IOS, and the resulting meshes were compared. In the mesh obtained with the IOS, the distance between two plans on the edge was approximately 100 micrometers, and that obtained with micro tomography was 25 micrometers. The curvature values were 27.46 (SD 14.71) μm^{-1} and 5.18 (SD 1.16) μm^{-1} for micro-CT and IOS, respectively. These results show a clear loss of information for objects that are less than 100 µm.

As there is no normalized procedure to evaluate the resolution of intraoral scanners, the method that we developed could be a positive parameter for the control of IOS performance by practitioners.

1 Introduction

IOSs appeared in dentistry in the 1970s and were used to scan the tooth surface and to prepare dental crowns [1]. The IOS is a medical device composed of a handheld 3D scanner (hardware) connected to a computer and software. The goal is to make precise three-dimensional measurements of an object in the mouth. The information collected by these IOSs is processed by powerful software that reconstructs the three-dimensional (3D) model of the desired structures [2] [3]. The most widely used digital open format for mesh is the Standard Tessellation Language (STL). Gradually, IOSs have entered dental clinical practice either connected to a digital milling machining [4] or connected via the Internet to prosthetic laboratories.

Presently, IOSs are used to obtain study models of prostheses [5] and to generate impressions necessary for the modeling and fabrication of a whole series of restorations, such as single crowns [6], fixed partial dentures [7], and in selected cases, complete fixed arches [8]. IOSs are also used in maxillofacial surgery, where the IOS is integrated in guided surgery procedures [9], and in orthodontics for the fabrication of aligners and different customized orthodontic devices [10].

Before the IOS is used, TiO_2 powder is required to eliminate light reflection and transparency; however, new models do not require this powder [11]. Nevertheless, in the case of surfaces that strongly reflect light, (such as metal crowns), powder coating could be required for correct imprinting.

An accurate 3D representation of the structure is the main objective of all IOSs [12]. Some questions related to the creation of a 3D mesh corresponding to teeth or a full arch are as follows: 1) What is the difference between reality and the 3D data acquired by the system and reconstructed by the algorithm? 2) What is the reproducibility level of the IOS? 3) What is the minimal detail size than can be recorded by an IOS camera? Will this minimum size allow the acquisition of small structures of the teeth such as perikymata? Should this size be related to the minimal detail needed to produce a clinically acceptable crown?

For the two first questions (corresponding to trueness and accuracy), several studies have been performed and published that provide some indication of the performances of IOSs; however, the third group of questions has not been addressed. Accuracy was defined in 1997 by the Joint Committee for Guides in Metrology (JCGM) as the "closeness of agreement between a measured quantity value and a true quantity value of a measurand", trueness was defined as "closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value", and resolution was defined as the "smallest change in a quantity being measured that causes a perceptible change in the corresponding indication" [12].

To evaluate the accuracy and trueness, studies compared 3D models reconstructed from IOSs and 3D reference models (obtained by a measurement machine, a high-resolution scanner or micro tomography). Variations among several acquisitions with an IOS provide information on the accuracy of the system, and the deviation between the IOS and reference acquisitions provides the trueness. For example, in 2014, a full arch with 14 abutments was digitalized with four commercial IOSs (iTero, CEREC AC Bluecam, Lava C.O.S., and Zfx IntraScan) and compared to 3D meshes obtained from an industrial scanner [13]. In 2012, a study was conducted on the accuracy of three intraoral scanners (Cerec, iTero and Lava COS) [14]. The distances obtained with intraoral scanners were compared with those obtained by an optical 3D measuring machine. A 2015 study used an epoxy model, and the reference was provided by micro-computed tomography (CT) [15]. The whole CAD-CAM chain, from intraoral scanning to 3D printing of the prosthesis with the production unit, was also evaluated [16] [17].

In 2017, a perfectly flat wafer was used to determine IOS noise, which is the sum of the practitioner and optical error, electronic noise and software parameters [20]. The measured roughness (RMS) of a perfectly flat surface is a valuable indicator for the noise of an IOS. A recent systematic review collected 32 studies on IOSs and concluded that accuracy is better with a low span of scanning on a surface with minimal irregularities [19].

A 2017 review of the literature surprisingly found that IOS resolution depends on "the cameras inside the scanner, which are generally very powerful" [20]. This finding emphasizes that there is no clear scientific study on the resolution of IOSs and that the only data available are given by manufacturers. Therefore, the aims of this study are to propose a reference object and to perform a set of calculations to evaluate the IOS resolution.

A reference form (ceramic tip), which was scanned by a reference system (micro-CT), was used. Then, this reference form was scanned with an IOS to evaluate the cropping of the IOS on the ridge line. This approach allowed the determination of the smallest element that the IOS can detect. The distance and curvature (which is an approximation of the second order of the surface and can be defined locally) were obtained.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Ceramic tip preparation

Vita Mark II feldspathic ceramic blocks (Vita Zahnfabrik, Bad Säckingen, Switzerland) for CAD-CAM systems were longitudinally sectioned using a high-speed diamond saw (Isomet 2000, Buehler, USA) to obtain 4 cm match-like specimens. Then, the specimen was cut 1 cm from the top, and the ceramic was beveled. The cut face was polished with abrasive discs with up to 1200 grit followed by polishing with diamond pastes of 0.25 and 0.1 µm particle size using a polishing machine (Escil, France). Thereafter, the samples were cleaned ultrasonically in a distilled water bath.

2.1.2 Intraoral scanner

The CS3600 IOS from Carestream (Rochester, New York State, USA) is a powder-free system. This is a confocal parallel system with a green laser light and a pinhole to select a focal plane. The light projected on the tooth is collected on a CMOS (complementary metal oxide semiconductor) consisting of a 1.3 cm sensor that transforms light into an electric signal. A motor quickly moves the focal plane, and a high intensity signal is collected to reconstruct the 3D mesh. During 3D recording, the intraoral scanner can capture HD photographs with 4 LEDs (blue, green, red, and UV) for realistic tooth reconstruction. The IOS was manipulated by a clinician experienced in CAD-CAM (Fig. 1).

2.1.3 Micro CT

X-ray tomography of the tip was performed with an EasyTom 150 kV system (RX Solution, Chavanod, France). The X ray source had a voltage of 70 kV and a voxel size of 5.4 micrometers, and an aluminum filter was placed front of the X ray generator.

2.1.4 Optical measuring machine

The Excel 502 Multisensor Measuring machine (Windsor, California 95492, USA) provides high-speed and accurate measurements. This instrument allows the measurement of 400x500x250 mm specimens with an x, y accuracy of (2.8+L/200) µm and a z accuracy of (3.0+L/100) µm, where L is the specimen length measured in mm, and a scale resolution of 0.1 µm. This machine was only used to evaluate the curvature of the tip on the edge; a 2D image was captured to approximate an order of magnitude of the sample.

2.2 Methods

2.2.1 Mesh extraction

The 3D mesh of the IOS was directly imported from the computer connected to the scanner via the operating software CS Restore (Version number 6.14.7.3, Carestream, Rochester, New York, USA). The 16-bit tiff microtomography slice files (1,315 files) were processed by Fiji software (v1 .51, National Institutes of Health, USA), and the threshold was determined using the gray shade mean value of the internal material of the tip. The images were then converted into an 8-bit format. The resulting image file was visualized with a plugin 3DViewer [21] in Fiji software that allows the computation of a 3D mesh corresponding to the surface of the scanned object in an STL binary file. To determine the threshold between the air and object, a mean value of the gray shade of object could be extracted from a the 2D tiff image in the Fiji software.

2.2.2 Data analysis

- *Mesh comparisons*

The alignment of the meshes (IOS mesh and micro-CT mesh) and the calculation of the distance were performed with CloudCompare software (version 2.10-alpha, EDF R&D, Paris, France). First, the best fit registration was automatically calculated with an algorithm by minimizing the distance between each mesh vertex. Then, the each vertex of the 3D mesh was projected onto the nearest face (triangle) of the reference mesh. The distance to the vertex was measured, and a color look-up-table was used to visualize the distances. Such a method allows us the visualization of the distances between the IOS and micro-CT meshes.

2.2.3 Method for resolution approximation

The resolution is the average the minimum distance between the two faces of the tip or the minimal curvature of the tip determined by the IOS device. To achieve this measurement, we have developed a set of two calculations.

- *distance between two tip faces*

No simple method exists to automatically select the vertex immediately before the curvature on the edges of the tip. The distances were calculated with the Meshlab software tool by the selection of the vertex of interest. To minimize error by the manipulator, 30 measurements were collected for each 3D image, and the means and standard deviations were calculated.

- *curvature calculation*

The curvature of the tip top was calculated with a function in Meshlab software using the discrete mean curvature of a normal operator given by the formula in a paper titled "Discrete Differential-Geometry Operators for Triangulated 2-Manifolds" [22]:

$$K(x_i) = \frac{1}{2A_{Mixed}} \sum_{j \in N_1(i)} (\cot \alpha_{ij} + cot\beta_{ij})(x_i - x_j)$$

where A_{Mixed} is a normalization term that represents the area defined for each vertex of a non obtuse triangle connected to the circumcenter point and for each vertex of an obtuse triangle connected to the midpoint of the edge opposite to the obtuse angle; a simple algorithm (pseudocode) allows full surface tiling; x_i is the position of the vertex where the curvature is evaluated, x_j is the difference in the first neighbors of vertex $N_1(i)$ and α_{ij} β_{ij} is the angle opposite to the segment formed by the vertices i and j [23] (Fig. 1.D). The curvature was calculated for the vertex of interest on the edge of the top of our object. The selection is represented as a red area, as shown in Fig. 1.A-B.

To avoid extreme values, the mean calculations were performed with a truncated value by discarding the 5th and 95th percentiles. Those values were compared with the value obtained with the optical confocal machine (Fig. 1.C).

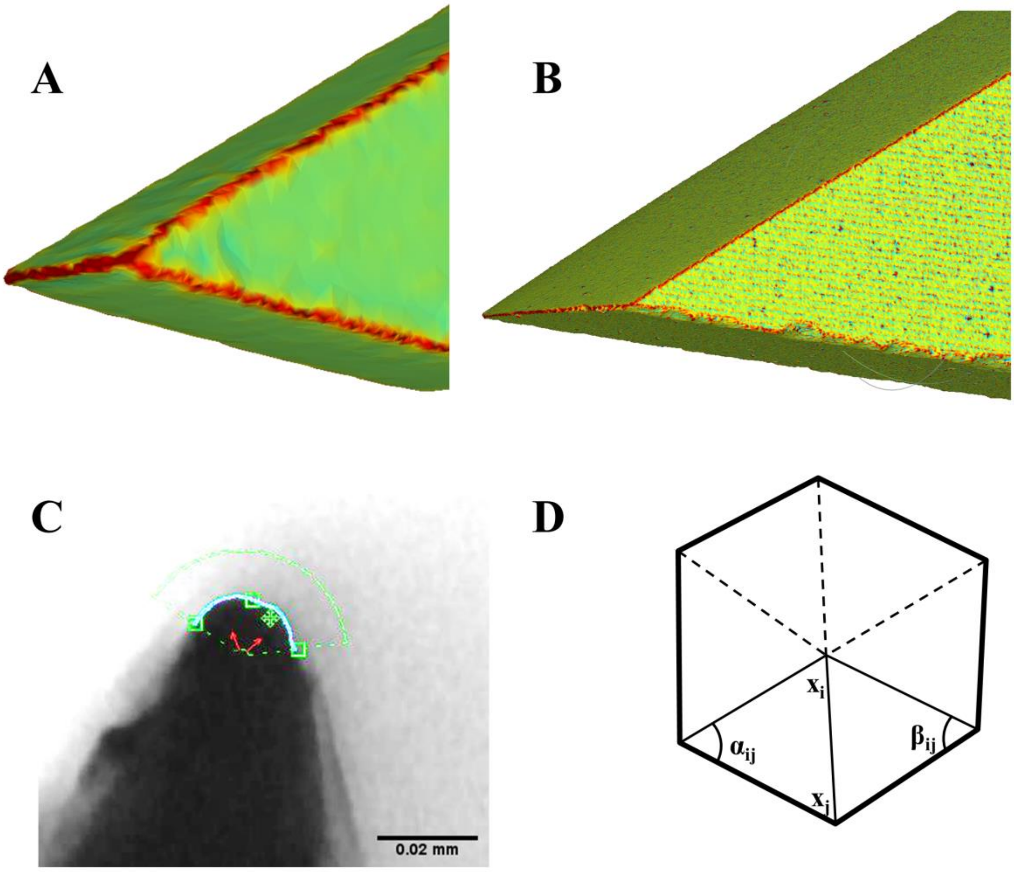

Figure 1

A, B) Mesh obtained using the IOS and micro CT, respectively; the red area corresponds to the highest curvature of the mesh, the green area corresponds to the flat part. C) Ceramic tip profile imaged with an optical measuring machine. D) Layout of a vertex and neighbors to explain the curvature calculation formula

2.2.4 Statistical analysis

To compare the distance and curvature results, we performed one-way ANOVA using Sigmaplot version 11.0 (Systat Software Inc, San Jose, USA).

3 *RESULTS*

3.1 distance between two tip faces

The mean, median and standard deviation (SD) of the distances between the upper and lower planes of the tip, which represent the smallest volume visible by the IOS or micro CT are presented in the top panel of Fig. 2. The mean of the micro CT measurements was 25.98 micrometers, and the values determined by the camera ranged between 89.67 and 124.28 micrometers.

Fig. 2 represents the results in the form of a table and a boxplot, emphasizing the different distributions and reproducibility of measurements of the same object with the IOS.

	a. Micro CT	**b. IOS test 1**	**c. IOS test 2**	**d. IOS test 3**	**e. IOS test 4**	**f. IOS test 5**
Mean (µm)	**$25.98^{b,c,d,e,f}$**	**$121.22^{a,d,f}$**	**110.61^{a}**	**$89.67^{a,b,e}$**	**$124.28^{a,d}$**	**$91.67^{a,b}$**
SD (µm)	**7.10**	**20.85**	**22.70**	**14.19**	**31.18**	**25.03**
Median (µm)	**24.50**	**118.50**	**109.50**	**89.50**	**124.50**	**86.00**

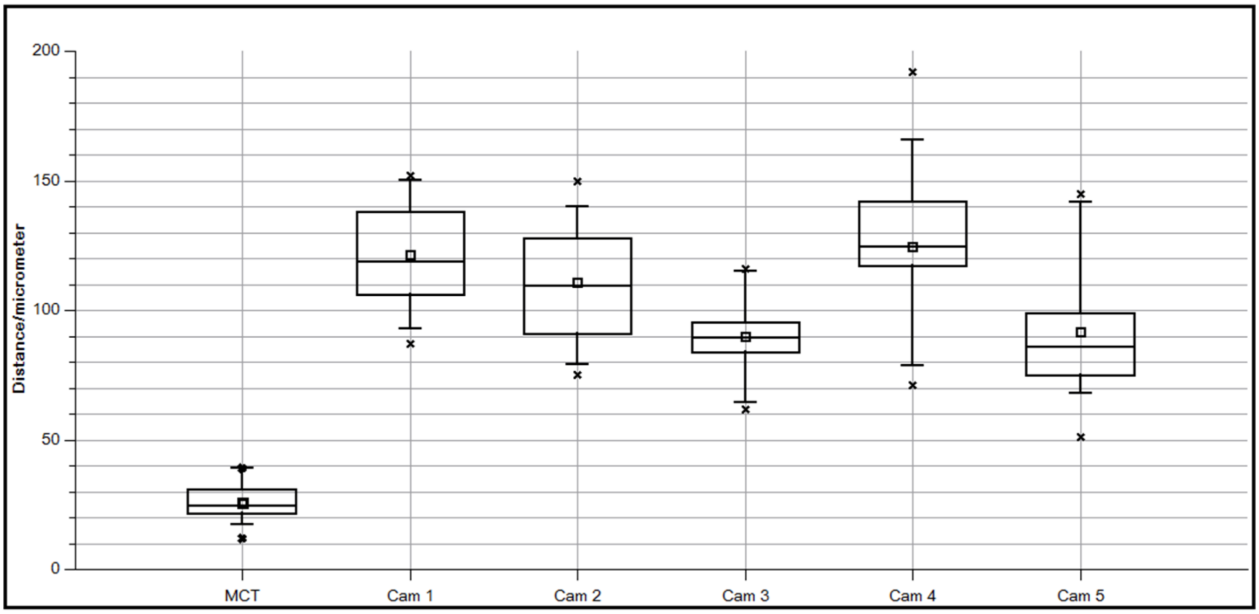

Figure 2

Table I: mean, SD and median distances between the two tip planes; superscript letters indicate a statistically significant difference. Box plot: distances between two planes of the meshes of the tip recorded by micro CT (MCT) and the CS3600 camera (IOS) for 5 different acquisitions (test 1-5) Rectangle: 25% to 75%. Whiskers: 5-95% range. Square: mean value. Point: min and max value.

3.2 Curvature

The curvature and the distribution of the mesh on the tip in the ROI (region of interest) are presented in Fig. 3. The 20% truncated mean of curvature for micro CT was 27.46 (SD 14.71) a. u., and the range was between 3.57 and 7.05 a. u. for the camera.

	a. Micro CT	b. IOS test 1	c. IOS test 2	d. IOS test 3	e. IOS test 4	f. IOS test 5
Truncated mean (μm^{-1})	**27,46**[b,c,d,e,f]	**4,79**[a,c]	**7,05**[a,e,f,b]	**6,23**[a,e]	**3,57**[a,c,d]	**4,29**[a,c]
SD (μm^{-1})	**14,71**	**2,79**	**3,56**	**3,96**	**1,54**	**2,13**
Median (μm^{-1})	**27,02**	**4,68**	**7,06**	**6,28**	**3,44**	**4,17**

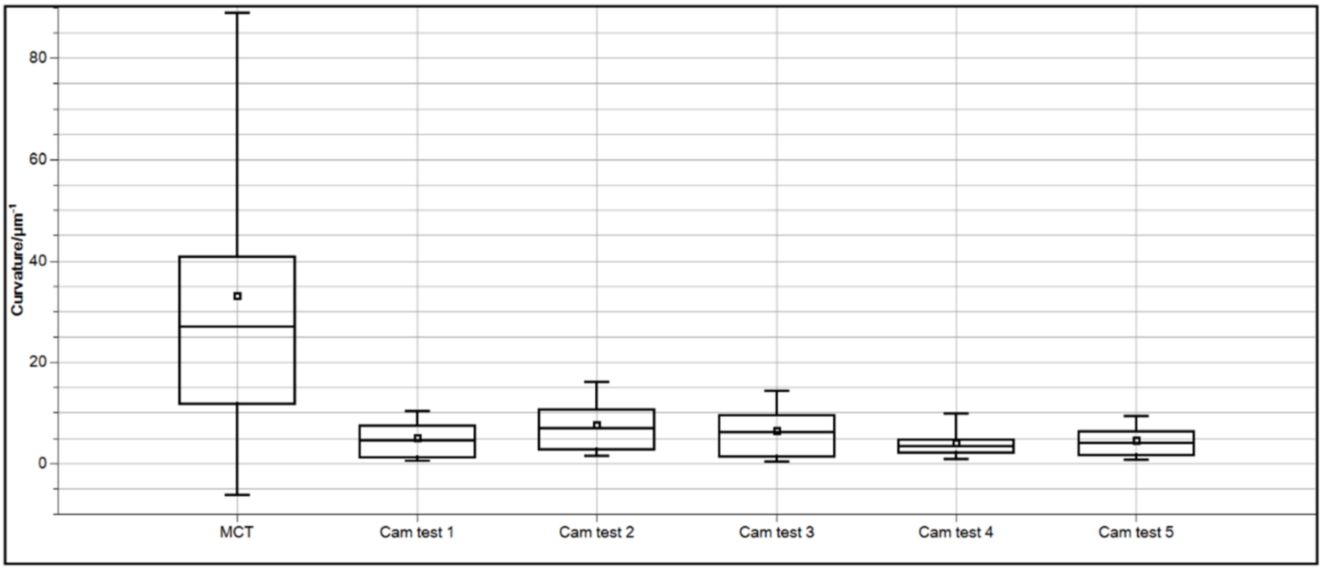

Figure 3

Table II: mean, SD and median curvature; superscript letters indicate statistically significant differences.

Box plot: curvature of the meshes of the tip recorded by micro CT (MCT) and the CS3600 camera (IOS) for 5 different acquisitions (test 1-5) Rectangle: 25% to 75%. Whiskers: 5-95% range. Square: mean value. Point: min and max value.

3.3 Mesh registrations

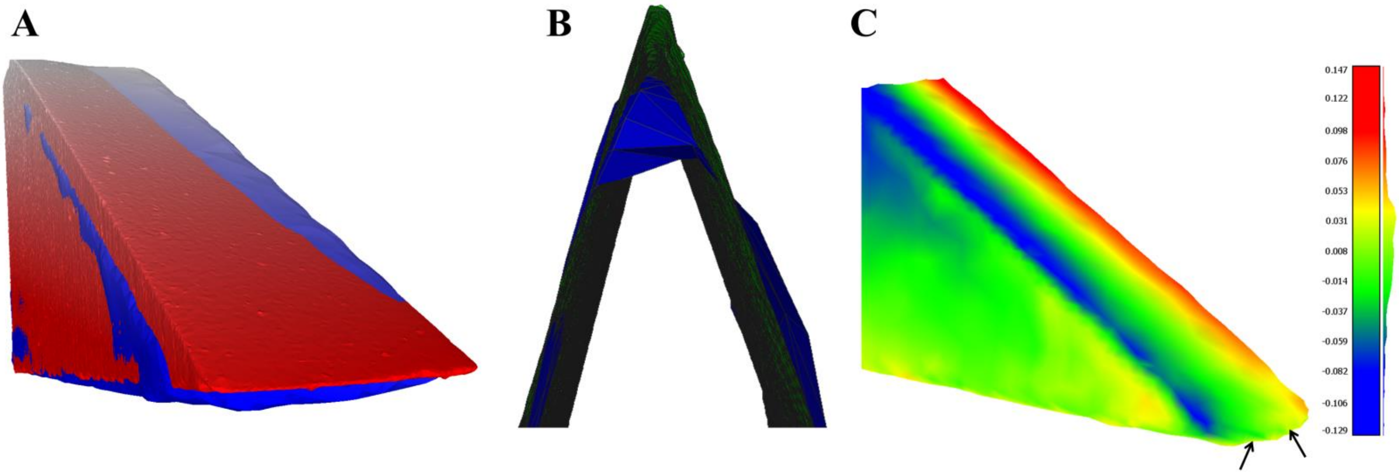

Figure 4

A: registration/superposition of the mesh recorded from the micro CT image and the CS3600 camera; B: detail of the superposition on a region of interest; C: colored map representation of distance calculated by projection of the camera mesh vertex on micro CT mesh faces. Black arrows: the distance values of interest.

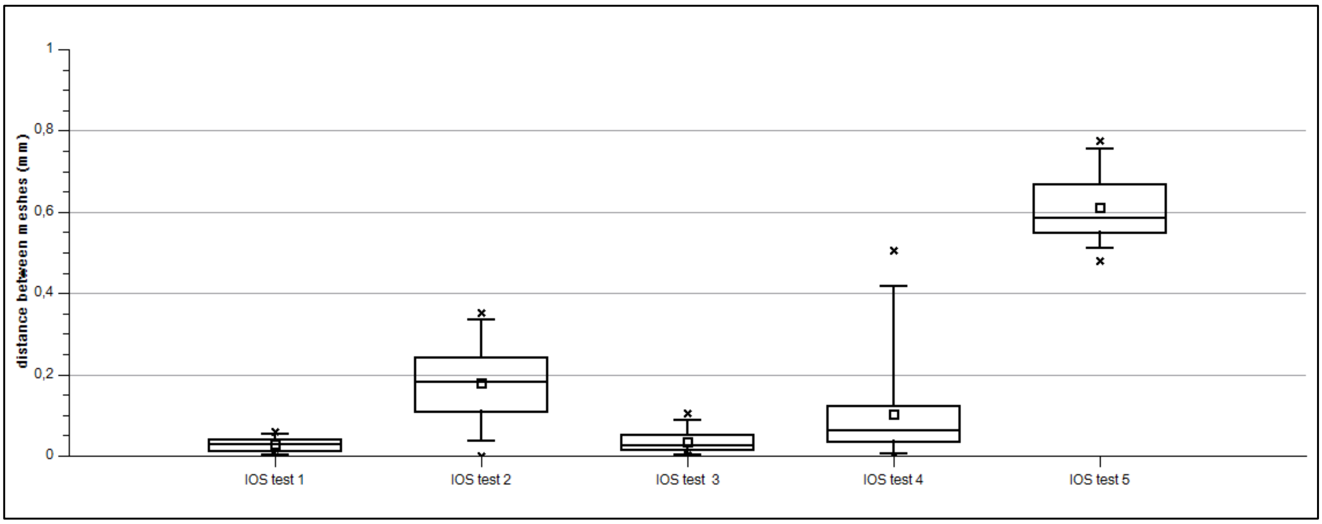

Figure 5

Distance between mesh for the micro CT (MCT) and the CS3600 camera (IOS) for 5 different acquisitions (test 1-5) Box plot: rectangle: 25% to 75%. Whiskers: 5-95% range. Square: mean value. Cross: min and max values. X axis: parameter acquisition (angulation and direction 1 or 2) and calculated area (W = whole mesh; CR = central region of mesh). Micro CT (MCT) and the CS3600 (IOS) camera were used for 5 different acquisitions (test 1-5)

3.4 Top view comparison

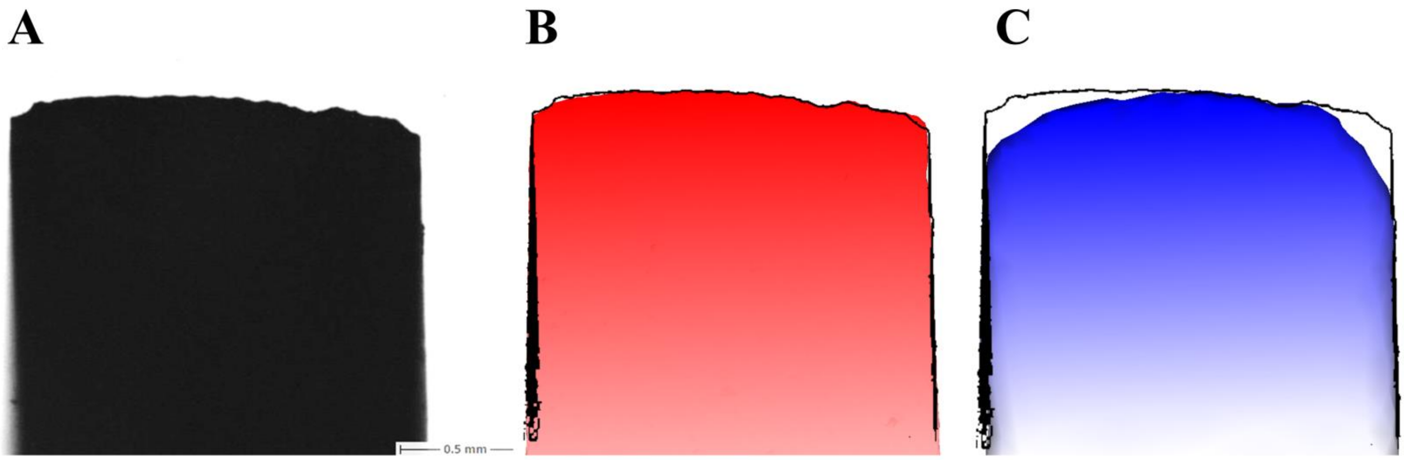

Figure 6

Top view of the tip visualized with A) an optical measuring machine, B) micro CT and C) the CS3600 camera. Black line in B) and C): the edge of the image obtained with the optical machine in (A). The blank in B) and C, corresponds to the difference between the optical measuring machine edge and the 3D image scanned with micro CT and the IOS and represents loss of information

4 DISCUSSION

-Resolution

IOSs and micro CT are systems used to discretize objects. In our model, the distance that separates the points at the end of each plane of the tip represents the resolution of the system studied. Indeed, the capacity of an IOS to reproduce the detail of a tip is equivalent to the minimal size that can be recorded. As shown in Fig. 2, this distance is 25.98 micrometers (SD 7.1) for micro CT, ranges from 89.67 (SD 14.19) to 124.28 (SD 31.18) micrometers for the IOS studied, and is 8.6 micrometers as measured with an optical measuring machine. We note the dispersion of the results for IOS acquisitions. This dispersion illustrates the difficulty in performing reliable acquisition with the IOS. Manual handling of the camera influences the results and alters the reproducibility and quality of the meshes obtained. This fact is supported by the p-value of the statistical test, as shown in the table in Fig. 2 (superscript letters). These results are very different from the resolution stated by the company. In the case of the CS3600 camera, no resolution was stated on the commercial document or the website of the Carestream Company; only the term “high resolution” was used. Those results, which greatly diverged from those of the optical measuring machine, could be explained by the acquisition method, which merged many images to create a complete mesh of the object. This method could smooth the angulations. The acquisition of an image at a high rate of speed, as recording a movie, encourages the use of such instrument by practitioners. First generation IOSs recorded individual images.

The smoothing of edges with the IOS is clearly visible in Fig. 6, where tips are oriented in the same "top view" for the three techniques: optical machine (A), micro CT (B) and IOS (C). Superposition of the image obtained with the optical measurement machine image, which is considered the closest condition to reality, and the two other techniques emphasize the edge smoothing produced by the IOS.
With these results, it is possible to study the roughness of teeth in vivo. Indeed, the perikymata are between 50 and 100 micrometers, and such structures are under the resolution established in this experimental setup.

-Curvature

The measures described above were confirmed with the curvature calculations detailed in Fig. 3. The distance values are linked to the curvature of the tip. The tip used in this experiment is not perfectly flat and smooth. The ceramic is very hard, and it is clearly visible on the confocal optical image of the tip profile that the top is jagged. The experimental difficulty in obtaining a perfect tip leads to extreme values in the mean curvature calculation. The values that correspond to negative curvatures are eliminated, and only the values that represent the round part of the top of the tip are selected. The distance that separates the two planes is large, and the curvature is small. As expected, the curvature on the tip in the micro CT mesh is clearly greater than the curvature observed in IOS meshes (p-value less than 0,05 for the comparison of the 5 tests with the IOS). This kind of measure has a large spread, as illustrated by the whisker position and the value of the SD reported. This finding could be explained by the inhomogeneity of the mesh in the region of interest; some points have first neighbors in a very flat localization or in a punctual negative curvature region. Therefore, the truncated mean is needed to avoid extreme positions.

-Registration

The method of registration between two surfaces in 3D must be discussed. Indeed, the results obtained represent the distance between the top of the tips in images obtained with micro CT and IOS. However, these results were difficult to obtain. In theory, such a method could approximate the loss of material that is not recorded with the IOS compared to the micro CT reference mesh. First, to register the two surfaces, the ROI must be cropped to obtain two similar meshes and to avoid error in calculation. This step is not automatic or performed by a rigorous methodology. The resulting numbers and sizes of triangles for a similar region are very different; with the IOS, 1167 vertices and 2280 triangles are recorded; with micro CT, 322 274 vertices and 673 401 triangles are recorded. The mean size of a triangle is 44 square micrometers with micro CT and 12 340 square micrometers with the IOS. Therefore, cutting of the two meshes to obtain a similar geometry could influence the result. Second, we observed that the tip register with the IOS is twisted compared to that of the micro CT. The problem of tip distortion by the IOS must be further studied.
The artifacts of IOSs have previously been highlighted by several studies that revealed many sources of distortions due to instability of the scanner or angulation problems [24].

IV. Conclusion

Our methods are the first to calculate the IOS resolution. These methods permit the development of a standard procedure to evaluate the performance of an IOS. Our results were obtained by calculating the distance between planes, which is correlated with the curvature of the tip and represents a good method for selecting commercial systems. The results demonstrate a clear difference between the actual object and the meshes obtained with the IOS and its associated software. The present paper is limited by the evaluation of the loss of information by the IOS due to the difficulties in obtaining good meshes registration with a twisted IOS mesh. A method is under study to automatically evaluate this performance with a finely parameterized object.

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Figure1

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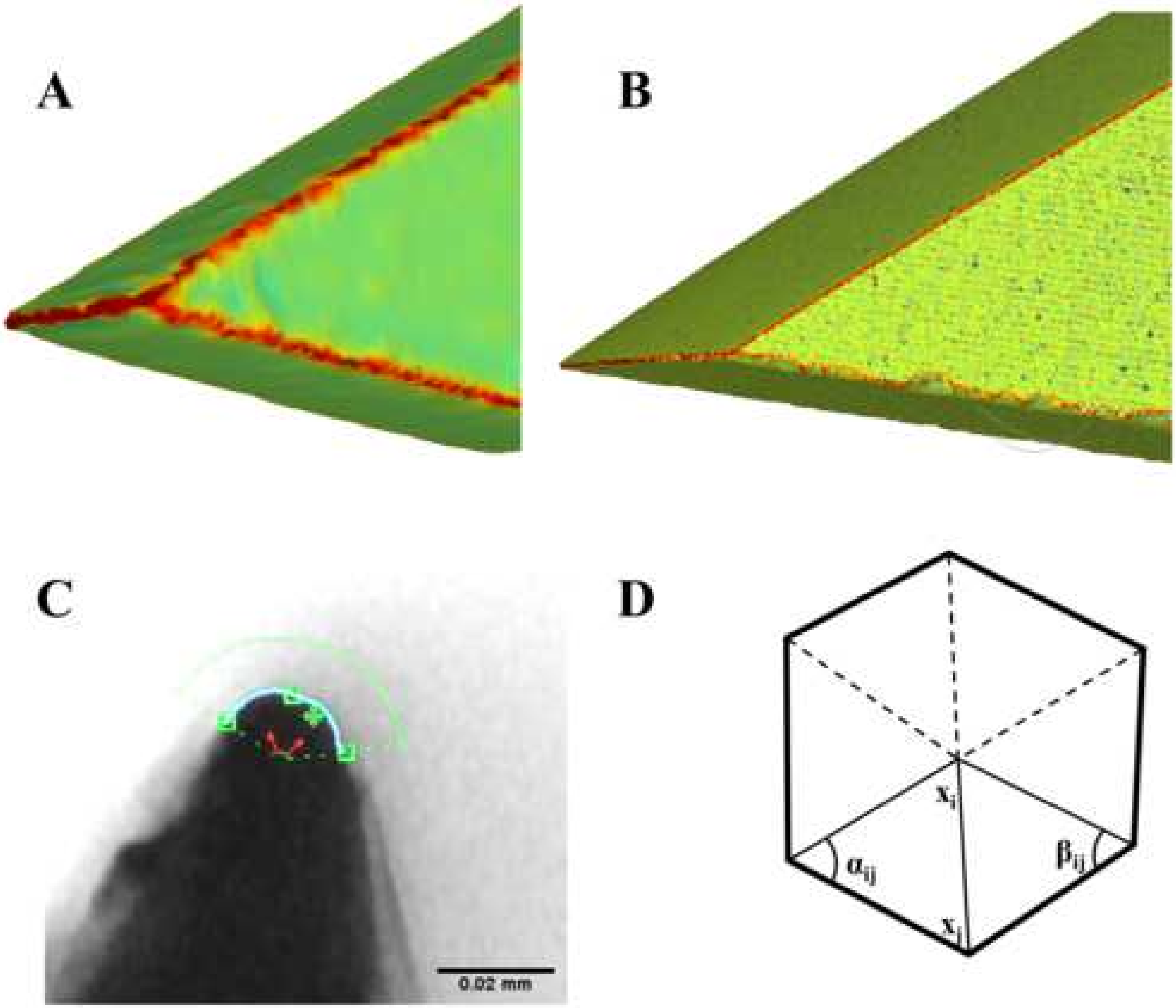

Figure2

	a. Micro CT	b. IOS test 1	c. IOS test 2	d. IOS test 3	e. IOS test 4	f. IOS test 5
Mean (µm)	25.98[b,c,d,e,f]	121.22[a,d,f]	110.61[a]	89.67[a,b,e]	124.28[a,d]	91.67[a,b]
SD (µm)	7.10	20.85	22.70	14.19	31.18	25.03
Median (µm)	24.50	118.50	109.50	89.50	124.50	86.00

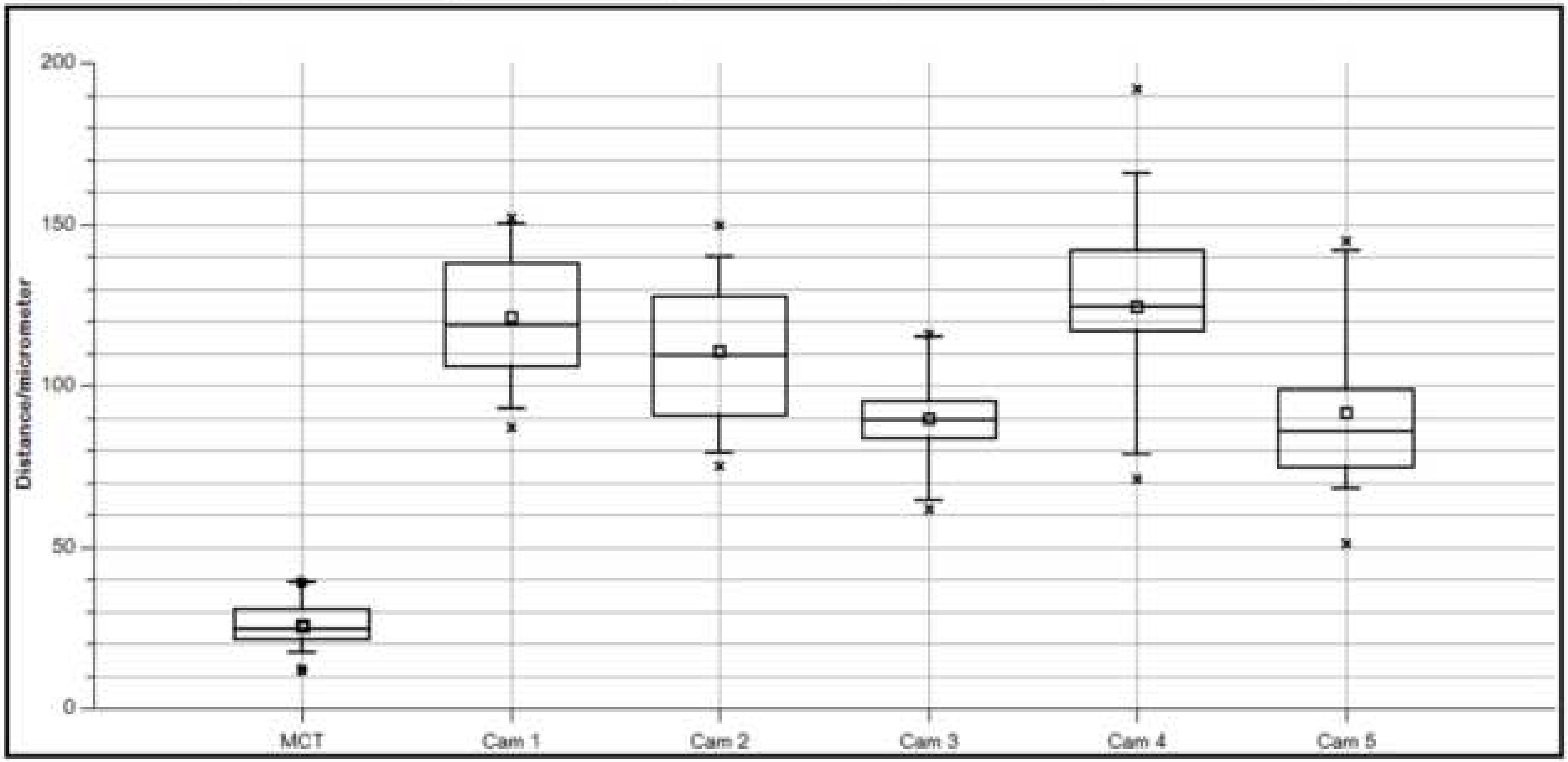

Figure3

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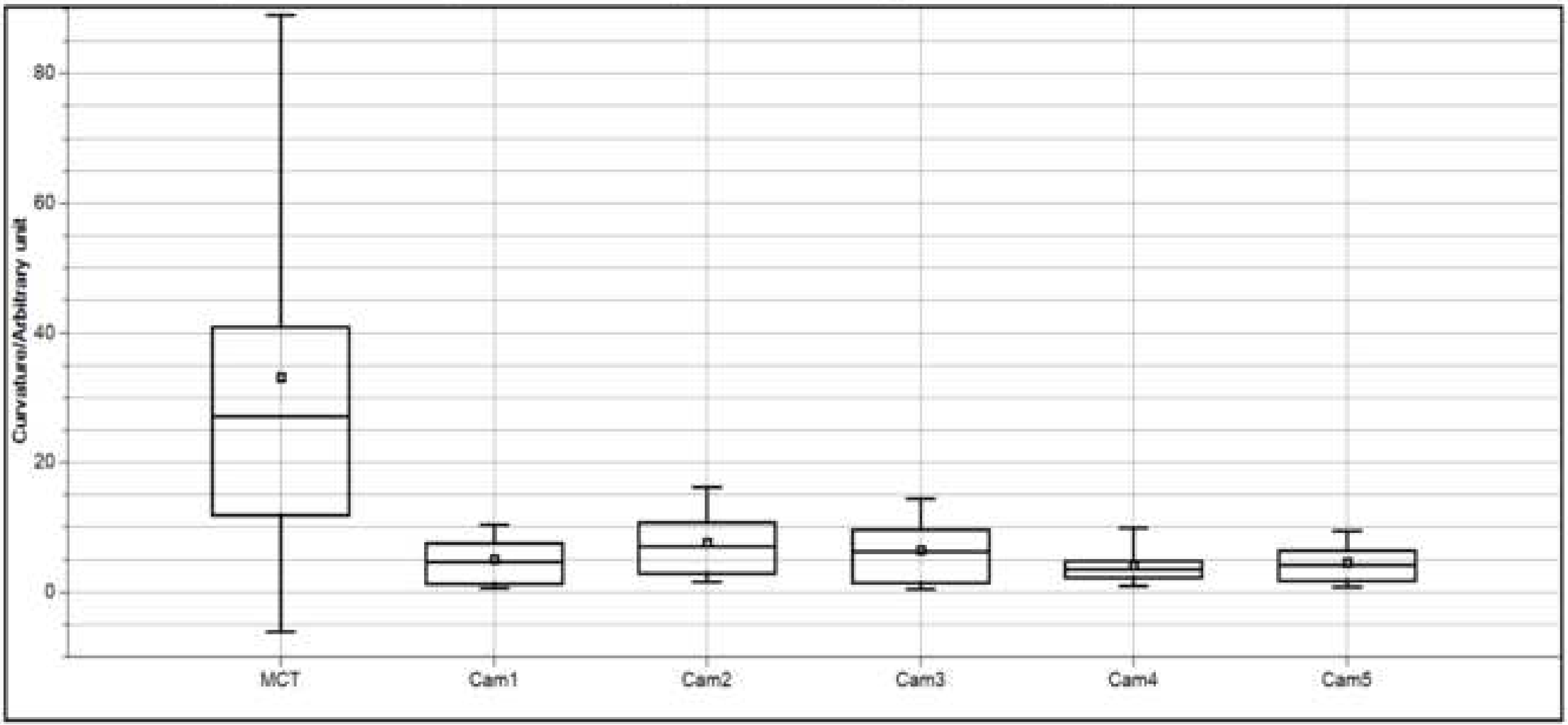
	a. Micro CT	b. IOS test 1	c. IOS test 2	d. IOS test 3	e. IOS test 4	f. IOS test 5
Truncated mean (µm)	27,46[b,c,d,e,f]	4,79[a,c]	7,05[a,e,f,b]	6,23[a,e]	3,57[a,c,d]	4,29[a,c]
SD (µm)	14,71	2,79	3,56	3,96	1,54	2,13
Median (µm)	27,02	4,68	7,06	6,28	3,44	4,17



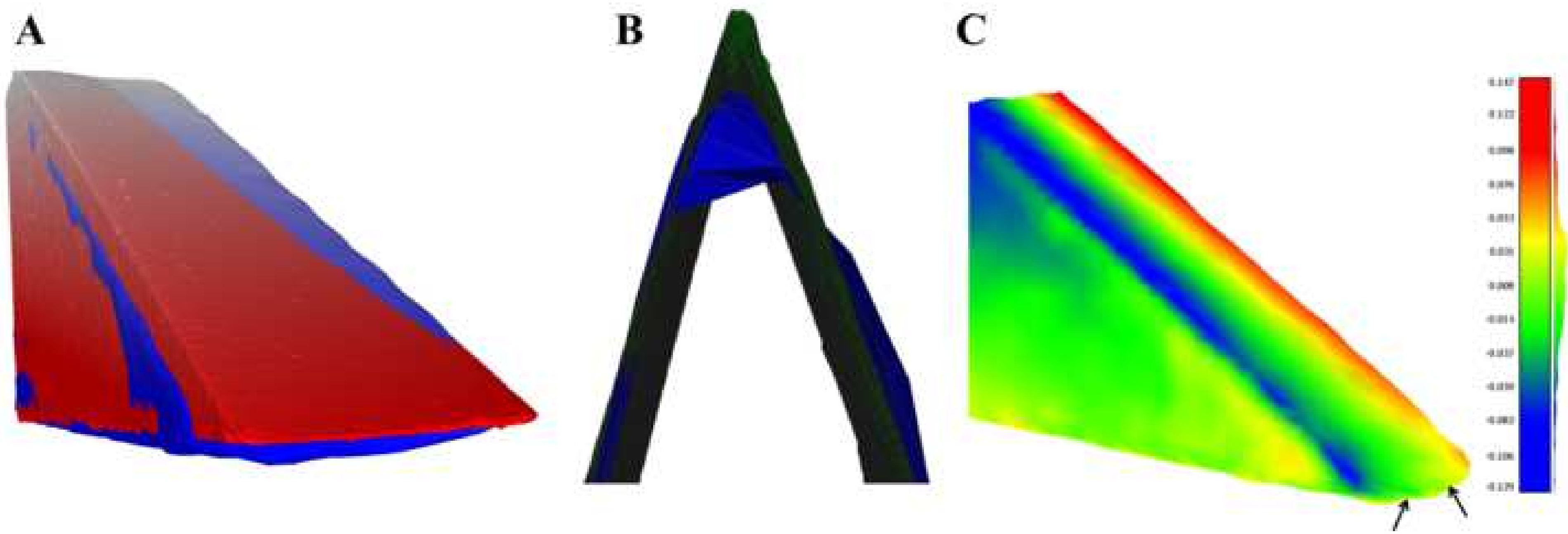

A
B
C

Figure5

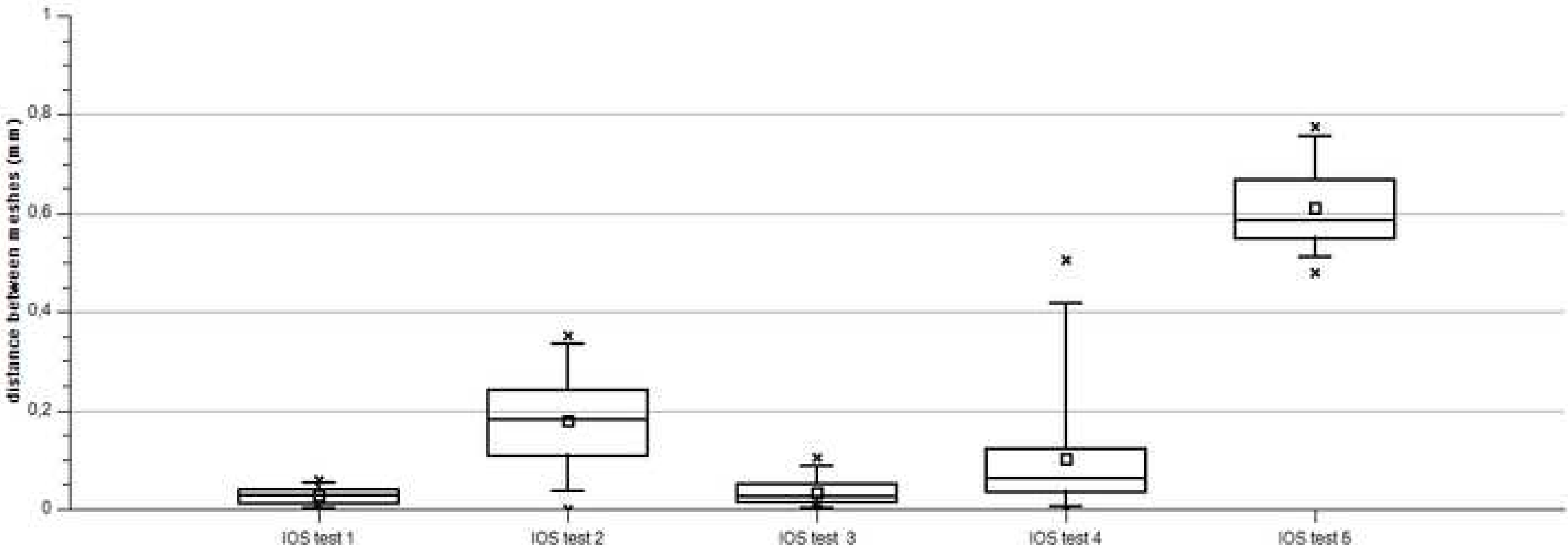

1
0,8
0,6
0,4
0,2
0
distance between meshes (mm)
IOS test 1
IOS test 2
IOS test 3
IOS test 4
IOS test 5

Figure6

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