Evaluation of the effectiveness and accuracy of digital techniques in the field of Restorative Dentistry

PhD dissertation

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1. INTRODUCTION

In the past decade, innovative manufacturing technologies, the use of modern materials and new clinical techniques have played a pioneering role in the development of so-called digital dentistry, expanding treatment options to all areas of dentistry.
Taking into account the particularities of the dental field, the benefits appear both on the medical side and on the patient side. Digital technologies have contributed to reducing the duration of interventions, spreading minimally invasive preparation techniques, and improving the psychological and physical comfort of patients. Digital tools have significantly changed diagnostic processes and represent progress in communication with patients.
The emergence of intraoral scanners (IOS) and advanced manufacturing processes enabled the widespread use of various metal-free dental materials, improving the functional and aesthetic results of restorations.

1.1. Development of CAD/CAM technology

In the past two decades, the use of computer-aided design and computer-aided manufacturing (CAD/CAM) technology in dentistry has developed rapidly. In 1983, restorative dentistry was revolutionized by the CEREC system, historically the first chairside CAD/CAM system.
According to the location of the manufacturing process, CAD/CAM systems can be divided into three categories: chairside systems, laboratory systems, and centralized manufacturing. In the latter two cases, upon completion of the dental work, the dental technician is responsible for the production of the restoration. In such cases, the patient must visit the dentist's office at least twice, compared to one visit for the chairside system. The main elements of CAD/CAM systems are: scanner, software (Computer aided design) and a milling machine or 3D printer (Computer aided manufacturing).

1.2. The role of digital dentistry in education

The use of digital technologies in dental curricula has begun worldwide. The biggest challenge in this is that you have to constantly adapt to the development of technology. When communicating with dental professionals, physicians, dental technicians, and providers, dental students must be prepared to manage digital data, ensure patient safety, and understand the benefits and limitations of traditional and digital processes.

Several locations around the world have implemented 3D dental education programs to enhance students' spatial visualization skills, interactivity, critical thinking, and clinical knowledge.

One possibility is "Virtual Reality" (VR), which displays the simulation using a specially designed headset. Another way is "Augmented Reality" (AR), where virtual elements can be displayed in the real environment with a phone or projector glasses. The use of the two technologies is valuable in both undergraduate and postgraduate education, as they provide an interactive learning opportunity with constant access and objective assessment.

The performance of the students improved during the digital design of a solo crown framework, they enjoyed the advantages of CAD/CAM technology, as the anatomical contours could be shaped precisely and viewing the enlarged digital plans improved the precise understanding of the task.

The use of IOS in simulation training showed that even inexperienced dental students can acquire the skills necessary for use and it was preferred over traditional impression taking.

The creation of complete removable dentures with a digital system resulted in excellently rated dentures, which were preferred not only by students but also by patients.

The objective nature of the digital assessment helps the development of students' visualization, provides immediate feedback, helps the teachers' evaluation and improves the students' self-evaluation and self-correction.

Digital tools are becoming more and more common in dental care, and this must be taken into account in curricula to prepare future dentists for their daily work. They can also play an important role in revolutionizing dental education, since the acquisition of appropriate knowledge and skills becomes available in various interactive and intuitive learning forms in a stimulating, more enjoyable and motivating way, with constant access.

1.3. The role of intraoral scanners

Intraoral Optical Scanners (IOS) are tools for making digital impressions in dentistry. A light source is projected onto the dental arch, including prepared teeth and implant scan bodies. The images captured by the light sensor are processed by the scanning software, which generates point clouds and then triangulates them, creating a 3D surface model.

IOSs work on different principles, which manufacturers often combine to minimize the noise generated during scanning, which is caused by the different translucencies of the oral cavity formulas, wet environments and unpredictable movements.

During active triangulation, the scanner projects a beam of light onto the object, and the distance to the object can be determined from the projection reflected from it. A camera consisting of a collecting lens and a position-sensitive photodetector detects the location of the laser spot on the illuminated object. The laser point appears in different places in the camera's field of view depending on the distance from the laser emitter.

The laser emitter, laser point and camera form a triangle. The distance between the camera and the laser emitter is known, this is the "baseline". The corner angle of the laser emitter and the camera is also known. The three data determine the shape and size of the triangle in relation to a focal length, so the depth of the object can be determined from the projection of the laser point on the plane of the detector.

This principle is used by CEREC Omnicam, Medit scanners and Planmeca Emerald.

IOS FastScan is the only system in which the camera moves, so the dentist only needs to hold the scanner in three positions for a complete image.

Scanners operating on the principle of "Confocal laser scanning microscopy" (CLSM) are based on the separation of focused and defocused images at selected depths. A laser beam is projected onto the surface of the sample with an objective lens, then the reflected light is guided through a focusing filter using a beam splitter, and only the image that falls into the focal point is displayed on the detector. The focal length is known, so the pixel distance can be calculated.
To scan the entire sample, a beam guided in a horizontal plane above the object uses servo-controlled oscillating mirrors.
The operation of the Trios, Primescan and iTero scanners is based on this principle.
The essence of scanners based on "active wavefront sampling" (AWS) technology is a disk with a single hole, located far from the axis of the lens, installed in front of the lens, which rotates quickly, so it is as if we see the image from two or more angles. The offset between the points on the images is proportional to the depth information.
In the case of images taken from several angles, the accuracy increases.
Lava (3M ESPE) IOS is based on AWS.

Optical coherence tomography (OCT) is an interferometric imaging technique in which the emitted light is split into two inside the device. One beam is reflected from a reference mirror, while the other is reflected from the sample to be examined. The length of the reference beam path is known. The two reflected beams interfere, if the length of the two beams is equal, they reinforce each other, if they differ by a distance of half the light wavelength, they cancel each other out.
With polychromatic light sources, the interference is reduced to a distance of micrometres, making it suitable for dental use.
The E4D scanner uses this operating principle.

Accordion Fringe Interferometry (AFI) is a revolutionary technology that extends traditional linear laser interferometry into 3 dimensions. Two coherent point sources illuminate the object, projecting an interference pattern onto it, which is captured by a high-precision digital camera.

The degree of apparent edge curvature, together with the known geometries between the camera and the laser source, allows the algorithms to digitize the surface of the object in 3D. They record the location of X, Y, Z surface points for each pixel.
The advantage is that it is less sensitive to background light and is not disturbed by a shiny surface either.
Lythos is an IOS operating on such a principle.

IOS, which is continuously being developed by VOCO, uses a new 3D scanning technique with a holographic approach based on infrared technology, the so-called "digital holography". In this way, it is able to map the contour of the subgingivally located tooth.
A VOCO által folyamatos fejlesztés alatt álló IOS infravörös technológián alapuló holografikus megközelítésű új, 3D scannelési technikát alkalmaz, ez az ún. „digital holography”. Ezáltal képes a subgingivalisan elhelyezkedő fog kontúrját leképezni.

1.3.1. Using dust while scanning

The light reflectance of dental tissues and other oral cavity substrates is not uniform. When scanning, this can be disturbed by the target area, the so-called point of interest (POI) detection and mapping. To avoid this, the scanning direction can be changed, a polarizing filter or a 20-40 μm powder coating can be used.
This technique has previously proven to be very accurate for small restorations, but it is uncomfortable for patients and requires more time. It is difficult to maintain the powder coating when scanning the entire jawbone. In previous studies, no clear difference was found regarding the accuracy of the scanning due to the effect of the powder coating.

1.3.2. Tracking and software

With 3D in motion digital impressions, the imaging process may be interrupted if the distance from the object is too great or the movement is too fast or uneven. Various software algorithms have been developed to solve this, which are mostly based on recognizing the geometry of the object. For this, the already scanned area must be rescanned, enabling the POI to be matched.

1.3.3. Spatial quality

The IOS software produces meshes of different densities, average density on flat surfaces and denser on curves.

The latest IOS also manage color and texture, increasing the scannability of teeth, the assessment of clinical situations and the user experience with photorealistic image synthesis, but this can also give a misleading image.

1.3.4. The concept and importance of the stitching mechanism

IOS have a limited field of view (FoV), one image does not cover the entire surface of the tooth. Images taken from different directions form overlapping regions, for which various algorithms have been developed for merging. This has errors that can accumulate as the scan progresses.

In addition to all this, the accuracy of the stitching is also affected by the scanning starting point and pattern.

1.3.5. Areas of use of intraoral scanners

IOS are used in most areas of dentistry, be it diagnostics, the production of restorations, dental prostheses, or unique devices, both during surgery and in orthodontics.

The marginal gap of single ceramic crowns and short-span restorations made in this way reaches a clinically acceptable level compared to those made on the basis of traditional impressions.

In the case of taking a precision impression covering the entire jawbone, the accuracy of IOS is still not sufficient.

Single implant crowns, short-span bridges and reinforcing bars can be successfully produced using optical impressions and scanbodies.

Making partial and full removable prostheses raises some questions due to the lack of reference points and the impossibility of registering soft tissue dynamics.

However, they can be used successfully for digital smile design applications.

With appropriate software, the scan can also be combined with CBCT files to create a model containing virtual bone tissue, to plan the position of implants and to create surgical templates.

1.3.6. Advantages and disadvantages

One of the main advantages of optical impressions is that it captures all fixed patterns without a physical impression, significantly reducing patient discomfort. They make it possible to reduce chair time, as an entire dental arch can be scanned in less than 3 minutes. However, the main time efficiency is most noticeable during the later work phases.

After the learning curve has peaked, it may provide additional clinical benefits. It becomes easier to take an impression in complex cases, in case of dissatisfaction there is no need to repeat the entire procedure. The evaluation and immediate repair are aided by the multiple magnification and the clearly visible intermaxillary relation, some software even indicates the undercut parts.

The need for material consumption is reduced, as there is no need for impression spoons, impression materials and sample preparation materials.

The dentist and the dental technician can assess the quality of the impression in real time, promoting more effective communication between the two.

The digital interface is also an effective tool for communication and marketing with patients.

The learning curve must also be taken into account when applying IOS, as a person who approaches the technological world with greater affinity can adapt it to everyday practice more easily than a dentist who is less receptive and interested in it.

In the case of digital impressions, the most common problems are the detection of deep preparation edges or the difficulty of scanning in case of possible bleeding.

These problems can be overcome by the use of a hemostatic preparation, and at the paragingival and subgingival preparation edges, sulcus widening thread or retraction paste and appropriate scanning technique.

Depending on the model, the purchase cost of the IOS can currently range from 6,500 to 35,000 euros. As the range increases, purchasing costs are expected to decrease, with the exception of high-end, last-generation models. The investment pays off best if the device is integrated into the workflows of the various dental specialties.
Purchase it is important to find out about additional costs such as updating the reconstruction software or, in the case of closed systems, making the extracted files universally usable, as manufacturers take different positions on these issues.

1.3.7. Basic concepts of accuracy

Accuracy describes the degree of agreement between the given measurement result and the real value of the object to be measured. Trueness shows the average deviation of the measurement from the real values, while precision (reproducibility) appears as the standard error of repeated measurements. These two independent factors determine accuracy, which is necessary for proper fit and virtual articulation of restorations.

1.3.8. Determining the accuracy of IOS

The measurement methods show the variability of the trueness and precision values, as they depend on many factors, such as the user, the instrument used and its calibration, the time between measurements and the external environment. Methods for calculating these values are limited due to the quality of the reference samples and the measurement techniques used. For this reason, further efforts are needed to develop standardized and comparable measurement strategies.

1.3.8. Comparison of accuracy testing methods

Indirect approaches examine the fit accuracy of a completed restoration, but cannot separate the manufacturing error from the scanner error.
The direct methods use comparisons on the surface of the dental arches after fitting 3D test samples using the best fit algorithm.

There are significant differences between in vitro and in vivo accuracy tests, the latter is difficult to determine because the reference master geometry cannot be digitized directly. In vitro tests can be carried out more simply and are a gateway to more in vivo-like tests.

2. OBJECTIVES

2.1. Examining the effect of the Dental Teacher system on students' preparation skills in the case of complex cavities

Examining the usefulness of the Dental Teacher preparation evaluation software as part of the preclinical education curriculum, which can improve the learning and development performance of university students preparing onlay cavities.

2.2. Investigation of the distortion caused by the stitching mechanism using a new methodology

In the case of pattern matching at the scanning origin, the determination of the deviation of the identical points per tooth and per scanning pattern. Determining identical points on an amorphous surface (teeth) may result in inaccuracy, so we determine the matching accuracy of the algorithm on individual teeth, which can be used to map the accuracy of the method.

2.3. Comparison of the distortion caused by the stitching mechanism with the new method, using 7 intraoral scanners and traditional impression-taking techniques ont he entire jaw bone

Comparison of the distortion occurring during intraoral scanning of teeth with the digitalization of the physical impression taking procedure.
Furthermore, the determination of the axis that is most affected by the stitching error during the entire jaw bone scan.
Finally, a comparison of the seven different IOS trueness values.

3. METHODS

3.1. Examining the effect of the Dental Teacher system on students' preparation skills in the case of complex cavities

A total of 36 dental students, each with 2 years of experience, were randomly selected from the quarter year. The students' task was to prepare an onlay cavity with mesio-occlusobuccal extension in the right upper first molar tooth of a plastic mulage. The demonstration of a pre-prepared master cavity was performed by a practice leader with extensive experience in inlay preparation.

Two drills of known dimensions were provided to prepare the cavity, diamond-coated inlay and fissure drills with rounded ends.

After a preparation time of up to 60 minutes, each tooth was digitized with a dental 3D scanner, which transmitted the data to the KaVo Dental Teacher® software for evaluation.

After the first preparation, the students were randomly divided into a control group and a test group, each consisting of 18 students.

Students in the control group received an oral evaluation, showing the defects with a dental probe, and then performed a second cavity preparation.

The instructor presented the first cavity formations of the test group on the 3D display interface of Dental Teacher and they were present during the measurements. After the evaluation, the second round of preparation was performed.

The final cavities of both groups were subjected to 3D scanning and then evaluated with the Dental Teacher software, and then the deviation from the ideal cavity was calculated before and after teaching.

The Mann-Whitney U test was used to analyze the comparison between groups. The deviation of the first preparations from the master sample and the relationship between the improvement was characterized by the Pearson's correlation coefficient. A linear regression line was fitted to the points, where the interaction showed the difference between the slopes of the two lines. The significance is almost 5% ($p<0.05$).

3.2. A Investigation of the distortion caused by the stitching mechanism using a new methodology

A maxilla and a mandible master model were created digitally with Zirkonzahn CAD / CAM software with 14-14 teeth (2-15 and 18-31, respectively, according to the universal designation). The models were produced by milling, from a PMMA disk and formed the basis of the test during the entire evaluation process. The master models were digitized with a high-precision industrial scanner to create the reference stereolithography (STL) samples (master - CAD body).

A digital impression of the physical models was made with an intraoral scanner using four scanning patterns. The starting point was the left second molar on both dental arches.

Scanning pattern "A" (SPA) with linear technique, moving from left to right over the occlusal surfaces up to the second molars, then continuing scanning from right to left on the lingual side, then moving over the occlusal surfaces from left to right, slightly tilting the scanner in the buccal direction. The impression was completed by mapping the buccal surfaces.

The linear technique is partially used for the "B" (SPB) and "C" (SPC) scanning samples, and completely for the "D" (SPD) scanning samples, the so-called was changed to "saddle technique". In the case of SPB, the samples were scanned linearly in the area of both molars and premolars, and in case of SPC, the molars, while in the other areas it was moved from the buccal side to the lingual side using a saddle technique until it reached the corresponding contralateral tooth.

All scanned samples were exported in open STL file format and then imported into the GOM Inspect software for evaluation. Here, a unique coordinate system was first set up, where the X (bucco-lingual), Y (mesio-distal) and Z (apico-coronal) axes were located along the occlusal and sagittal planes. Two measurement points were determined on each tooth of the master sample. The master and test samples were joined together by the software along their entire surface, then local matching was performed in 14 places per dental arch using the so-called According to the "local best fit" algorithm, identical points were matched to each other on the two samples. Then the zone corresponding to the scanning origin was reactivated. The deviations of the measurement points of the test samples from the master samples were registered in the software in millimeters along the X, Y and Z axes.

When analyzing the data, three methods were compared: the first value (total surface deviation) was the average distance between the surface points closest to the measurement points, which is automatically determined by the GOM software and is the most common method in the literature. The second value was calculated from the 3D distances between identical points during full surface matching (total identical point deviation). The third, new method developed by us (origin identical point deviation), the average absolute deviation between identical points, calculated for the entire dental arch, was calculated after the alignment at the scanning origin.

The three values were compared in a generalized linear mixed model, with a gamma distribution and a log-link function. The p values were adjusted using the Bonferroni method, compared pairwise with an alpha set at 0.05. Correlations between the methods were evaluated using the Spearman test.

3.3. Comparison of the distortion caused by the stitching mechanism with the new method, using 7 intraoral scanners and traditional impression-taking techniques ont he entire jaw bone

For the sake of accurate modeling, a maxilla from a fresh human cadaver with preserved dentition formed the test sample. During the entire duration of the study, the dissected maxilla was kept at 4°C and moist in order to preserve the condition of the tissues. The maxilla was digitized with an industrial 3D scanner and served as a master sample in the comparison. Seven different IOS were selected for the study: Trios 3, CEREC Omnicam v2., CS 3600, iTero Element 1 and Element 2, Planmeca Emerald, PlanScan.

Each was scanned five times by a single user who was experienced with the system and used the scan pattern recommended by the manufacturers, all starting at tooth #15.
The scan included all teeth, the proximal areas of the prepared surfaces, the gingival areas and the palate.
In addition, five traditional polyvinyl siloxane (PVS) impressions were made, using a two-phase-simultaneous technique, with factory spoons. From these, extra-hard, high-strength plaster castings were used to make precision samples, which were digitized with a dental laboratory table scanner with the highest accuracy (50 μm) in order to reproduce the traditional work process.
All test files were exported in STL format and then imported into the GOM Inspect software.
To determine the trueness value, the deviation of the test and master samples was examined using the origin identical point deviation method. After setting up the appropriate coordinate system on the master sample (X, Y and Z axes on the occlusal and sagittal planes), two measurement points were selected on each tooth at specific locations, which served as reference points (28 points).
They were evaluated individually for the intraoral scan. In the first step, an automatic superimposition was performed on the master sample, then the boundary line of each tooth was circled so that the chosen identical measurement points could be identified and matched for each tooth with the "local best fit" algorithm. When the two samples matched each other tooth by tooth, the two corresponding points were copied from the master to the test sample (identical points). Finally, the alignment of the two samples was restored to the scanning origin. The deviation values between identical points were registered along all three axes of the corresponding coordinate system. The average complex deviation shown in 3D was calculated from the vectors of the 3 axes based on the Pythagoras theorem.
The complex 3D deviation from the tooth-by-tooth master pattern (trueness) was measured along the scanning direction of the entire dental arch, which shows the accumulated deviation due to stitching.
The deviation along each axis was statistically compared in order to

measure the axis with the greatest deviation. The scans started on the occlusal surface, and this view was assigned to the Z axis, so the deviation here indicates an error in the depth measurement.

Complex 3D discrepancies between teeth were averaged and then compared between IOSs and between IOSs and digitized samples of the physical impression. This average value shows the general trueness value of the scanners, while the standard deviation shows the precision value (ie reproducibility).

The data were imported into the SPSS 25 program for statistical analysis. Deviation values were analyzed with a generalized liner mixed model, gamma distribution and log-link function, with restricted maximum likelihood estimation. In the first model, the complex deviation values (combinations of the absolute values of the three vectors, X, Y, Z) were analyzed with two main factors, the teeth and the scanners, and their interaction. In the second model, differences measured separately on the three axes were examined, including the main effect of the interactions between scanner and axis and scanner x axis. To avoid an increase in first-order error caused by multiple pairwise comparisons, p values were kept at the 0.05 level using the Sidak method. The standard deviation of the complex deviations averaged over the teeth, which gives information about the precision value, was statistically evaluated using the F-test, applying the Bonferroni correction.

4. RESULTS

4.1. Examining the effect of the Dental Teacher system on students' preparation skills in the case of complex cavities

In the case of the test group, all measured parameters showed an improvement trend. The deviations of the average OD, AD and SW from the master sample were significantly smaller in the case of the second cavities.

The improvement of the average SW parameter was significantly higher in the test group.

A significant correlation was observed between the improvement achieved from the first to the second preparation and the deviation measured at the first preparation for both groups.
In the test group, the intersection point and slope of the y-axis of the regression equation were significantly higher than in the control group. This means that the overall improvement measured in the second preparation in the test group was better compared to the average first preparation value. The higher slope indicates that the students who performed worse in the first preparation had a greater improvement in the test group.

4.2. Investigation of the distortion caused by the stitching mechanism using a new methodology

We wanted to estimate the error of determining the identical points from the average surface deviation of a toothed joint. The average deviations ranged from 23 to 46 μm. It was lower in the upper arch than in the lower arch. The scanning pattern had no effect on the deviation.
For the examination of the change of the origin identical point deviation per tooth and per scanning pattern, two-way tooth x pattern and tooth x side interactions were plotted for the sake of graphical representation. The significant interaction between tooth and pattern suggested that the deviations for each tooth differed from pattern to pattern. The interaction between side and tooth was significant for the X and Y axes, but none for the Z axis. The difference in the deviation between the sides along the X and Y axes varied from tooth to tooth.
On the maxilla, on the X-axis, the SPC and SPD points gradually deviated towards the contralateral side, while the SPA and SPB deviated to the left on the ipsilateral side and to the right on the contralateral side. On the Y axis, all measurement points gradually deviated in the ventral direction. Deviations from the midline were significantly greater in SPA and SPB than in SPC and SPD. All measurement points along the Z axis deviated coronally up to the center line of the sample, from there the degree of deviation did not

increase in SPA and SPB. Teeth #11 - #6 had the largest deviation at SPA.

On the lower jaw bone, all measurement points on the X axis deviated towards the opposite side. The difference in SPA was significantly lower in teeth #29 - #31, but similar in teeth #19 - #28 compared to the others. At the Y axis, all measurement points deviated ventrally. The deviation of SPA was significantly lower than that of SPB in teeth #29 - #31 and less than that of SPD in tooth #31.

All measurement points along the Z axis progressively deviated in the coronal direction until the center line, from there the deviation gradually approached the initial zero point. All the differences were greatest in the case of SPA and to a lesser extent in SPB, SPC, and SPD.

In the case of the upper dental arch, there was a difference between the oral and vestibular measurement points on the X-axis only between teeth #6 and #9, while in the lower dental arch, tooth #27 showed a difference along the X-axis and teeth #24 and #25 along the Y-axis differences were observed.

There is a significant difference between the three different pattern matching methods regardless of the dental arch and the scanning pattern. The aggregated average deviation between identical points, which was calculated according to the alignment at the scanning origin, was significantly higher than the average deviation obtained during the approximate alignment of all surfaces, as well as a significantly higher value than the average deviation between identical points in the case of alignment of all surfaces. Also in the case of full-surface fitting, examining all the points of the entire surface, the total average deviation value was significantly lower than the average value of the identical points.

The comparison of the scanning patterns with the matching at the scanning origin showed that in the case of the upper dental arch, SPD showed a significantly smaller deviation than SPA, but it was similar to SPB and SPC. In the lower dental arch, SPD showed significantly less variation than SPA and SPB, but was similar to SPC. With the other two fitting methods, no statistical difference can be observed for any of the dental arches. A significant correlation was found between the deviation measured at the scanning origin and the average total dental arch deviation, as calculated by any of the three methods. The correlation was also significant between the two surface matching methods (surface-full and ident-full), however, there was no correlation between the ident-orig and surface-based matching methods.

4.3. Comparison of the distortion caused by the stitching mechanism with the new method, using 7 intraoral scanners and traditional impression-taking techniques ont he entire jaw bone

Examining the complex 3D deviation per tooth in the first model, both the main effects, the tooth, the scanner, and their interaction were significant. The values increase continuously starting from the direction of the scanning origin, and this trend level can be observed in all IOS, with the exception of Element1 and Element2, where it starts to decrease in the anterior region. The most significant deviation was detected in the case of PlanScan.

The total surface deviation is barely visible without taking into account the scanning origin, in contrast to the "local best fit" fitting performed at the scanning origin. The 3D image of the tooth farthest from the origin (#2) clearly shows the cumulative distortion caused by the deviation between identical points. This is much greater than the difference between the surfaces. The increased deviation from the scanning origin to the end point is not visible in the sample made based on the physical impression.

In the first statistical model, the significant scanner main effect refers to the difference between scanners regardless of tooth-by-tooth variation. Based on the paired posthoc analysis, the deviation of the physical sample was significantly lower than the value of most scanners, with the exception of Trios 3 and CS 3600. The deviation of Trios 3 was significantly lower than that of PlanScan and Emerald, and the value of Omnicam was lower, like the values of PlanScan and Emerald. Element 2 and Emerald had significantly

lower deviation values than PlanScan. The CS 3600 was not significantly different from other scanners.
The lowest precision occurred with the physical sample (20 µm). Compared to this, all IOS had a significantly higher standard deviation. Trios 3 (89 µm), Element 2 (123 µm), Omnicam (125 µm), Emerald (166 µm), Element 1 (300 µm), CS 3600 (326 µm), PlanScan (561 µm). This order roughly corresponds to the order of the trueness values. The standard deviation of PlanScan was significantly higher than the value of Trios 3, Element 2 and Omnicam.
Examining the deviation per axis, the scanner, axis and their interaction were significant in the second model.
Overall, the mean deviation (over the entire dental arch) on the Z-axis was significantly higher than on the X-axis and the Y-axis. The significant scanner x axis interaction indicates that there is a difference between the IOSs in the deviations per axis. In the case of most IOS, the deviation for the entire dental arch was the largest along the Z axis, while the values for the other two axes were similar. The exception is the Planmeca devices (PlanScan and Emerald), where the X-axis deviations were similar to the Z-axis values.

5. CONCLUSIONS

Within the limits of the Dental Teacher study, it was proven that the preparation analysis system can improve the students' learning curve in the case of a complex cavity preparation task. Furthermore, it provided valuable help to the students in learning the appropriate dimensions of preparation.
The new method we developed and proposed for measuring the accuracy of IOS can be more sensitive than any of the previous methods, which significantly underestimate the deviation. It can be used to understand the effect of tooth surfaces, the IOS technique and scanning patterns, especially in the case of a full arch application. It is recommended to examine the deviation between scanners with different hardware and software in case of a complete dental arch. The present

method highlights that the most sensitive point of 3D recording is the triangulation measurement, so this information allows manufacturers to improve the performance of their IOS technology.
This innovative measurement technique was further confirmed by indirect scanning of the physical impression, since while the stitching error is one of the weakest points of the IOS, it does not affect the lab scanners. The method can contribute to a more sensitive detection of statistical differences between the trueness values of the scanners. The biggest deviation of the IOS occurs in the depth measurement. In the case of a human cadaver, the physical impression of the entire dental arch turned out to be the best and most accurate, however, the relatively newer IOS systems (Trios 3, Omnicam, Element 2, Emerald) have clinically acceptable results.

6. LIST OF AUTHOR’S PUBLICATIONS

6.1. Publications related to the dissertation

Nagy Zs; Simon B; Mennito A; Evans Z; Renne W; Vág J
Comparing the trueness of seven intraoral scanners and a physical impression on dentate human maxilla by a novel method BMC ORAL HEALTH 20 : 1 Paper: 97 , 10 p. (2020)
Nagy Z; Vág J; Mennito A; Renne W
Comparison of distortion of seven intraoral scanners caused by stitching mechanism BMC ORAL HEALTH 19 : S1 Paper: P16 (2019)
Vág J; **Nagy Zs**; Simon B; Mikolicz Á; Kövér E; Mennito A; Evans Z; Renne W
A novel method for complex three-dimensional evaluation of intraoral scanner accuracy
INTERNATIONAL JOURNAL OF COMPUTERIZED DENTISTRY 22 : 3 pp. 239-249. , 11 p. (2019)

Vág J; Kövér E; Mikolicz Á; **Nagy Z**

Assessment of distortion caused by stitching during full arch intraoral scanning BMC ORAL HEALTH 19 : S1 Paper: P15 (2019)

Nagy ZA; Simon B; Toth Z ; Vag J
Evaluating the efficiency of the Dental Teacher system as a digital preclinical teaching tool. EUROPEAN JOURNAL OF DENTAL EDUCATION 22 : 3 pp. e619-e623. , 5 p. (2018)

Vág J; **Nagy Zs**; Simon B; Tóth Zs
Use of a preparation validating software (Dental Teacher® - KaVo) for pre-clinical teaching method enhancing learning procedure and performance
In: White, Deborah (szerk.) Science and the Competent Dentist an Inter-professional Perspective
(2016) p. 23

6.2. Dissertation-independent publications

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