SEMMELWEIS EGYETEM

DOKTORI ISKOLA

Ph.D. értekezések

3207.

SCHMALZL JUDIT

Fogorvostudományi kutatások

című program

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Factors affecting the accuracy of intraoral scanners

PhD thesis

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Budapest

2025

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List of Abbreviations

FDP – fixed dental prosthesis

FoV – field of view

IOS – intraoral scanner

IPC - iterative closest point

IQR - interquartile ranges

NPAL – the scanning did not conclude the palate

PAL – the scanning concluded the palate

PMMA - polymethyl methacrylate

SD – standard deviation

SPG – stereophotogrammetry

STL - Standard Triangle Language

RMS – root mean square

WHL – whole deviation

2D – two-dimensional

3D – three-dimensional

1. Introduction

Conventional impression techniques have been utilized to record the 3D geometry of soft and hard tissues of the mouth since the 17th century [1,2]. However, volumetric distortions inherent in impression materials and casting procedures introduce potential inaccuracies, necessitating a meticulous, multistep workflow that requires coordinated cooperation between a skilled clinician and a dental technician [1–3]. The advent of digital dentistry, which can be traced back to the early 1980s, has led to continuous advancements in the field, with digital workflows becoming an integral component of contemporary dental practice. Among the most transformative innovations is the appearance of intraoral scanners (IOSs), which facilitate a seamless transition into digital impression-making [4,5]. The increasing adoption of digital dentistry is driven by its effectiveness in facilitating accurate diagnosis, streamlined treatment planning, and the fabrication of orthodontic appliances and prosthetic restorations [6]. IOSs, recognized as instruments for acquiring optical impressions, functions by projecting a structured light source onto the dental arch. The imaging sensors capture the reflected data, which is then processed by scanning software to generate a point cloud representation of the scanned tissues [5,7]. The acquired data is typically stored in a standard tessellation language (STL), wherein triangulated surfaces represent the scanned structures [8,9]. The increasing implementation of digital workflows, including intraoral scanning, has been shown to enhance efficiency and reproducibility in clinical and laboratory settings [8–10].Comparative analyses indicate that the accuracy of conventional impressions and laboratory-based scanner systems are comparable to that of intraoral scanning for short-span impressions [11,12]. Although, discrepancies in accuracy have been found in the context of full-arch digital impressions [5,13]. Given that the accuracy of digital impressions is a critical determinant of the long-term clinical success of definitive restorations, the integration of IOSs represents a pivotal advancement in modern prosthodontics and restorative dentistry.

1.1 The definition and meaning of accuracy

In accordance with ISO 5725, accuracy is defined as a combination of precision and trueness [14]. Accuracy refers to the deviation between the measured quantitative values and the actual spatial dimensions of the object being assessed [15]. Precision denotes the consistency of repeated measurements on a given target, while trueness describes the degree to which a measurement corresponds to the actual values of the measured object [16]. Using a target as an illustration, we can observe the relationship between accuracy, trueness, and precision. If the arrows are dispersed both far from each other and from the center of the target, both trueness and precision are low. If the arrows are clustered together but positioned far from the center, precision is high, but trueness is low. Conversely, if the arrows are scattered yet relatively close to the center, trueness is high, but precision is low. High accuracy is achieved only when all arrows are closely grouped at the center of the target, indicating both high precision and high trueness. (Fig.1.)

Figure 1: Visualisation of accuracy

1.2. Measuring accuracy

During the accuracy assessment, a highly precise industrial or laboratory scanner is typically used to create a reference dataset. Industrial scanners were used widely, and it was also proved later that laboratory scanners are also satisfactory for creating a reference [17]. This dataset is then compared with both digital and analog scans using a specialized program, such as Geomagic Verify, Geomagic Control X or GOM Inspect. The two surfaces can be superimposed in the program and several comparison methods can be implemented [18]. (Fig. 2.)

The most widely used approach for examining the deviation of the STL files is the best-fit alignment method, in which the reference and measurement datasets are aligned by the

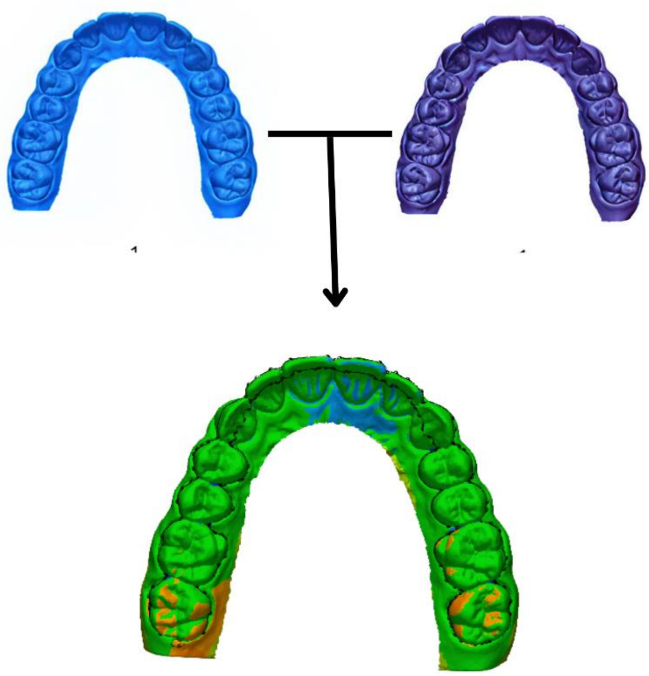

Figure 2: Superimposition

computer program. After an initial alignment, when the alignment is conducted to match the coordinate system of the scan data with the nominal data, the best-fit alignment helps to find the best overall alignment using an iterative closest point algorithm (ICP) [19,20]. This method was first introduced by Chen and Medioni in 1991 and has undergone several improvements since then. Its advantage lies in visualizing positive and negative differences between the samples through a color map [21]. However, it disregards the starting point of the scan and does not measure the deviation frame by frame across the entire maxilla. As a result, it fails to account for software alignment errors, which can ultimately lead to significant inaccuracies [22,23].

Another method involves measuring the linear distance between two defined points on both the reference sample and the samples taken during measurements, followed by comparing these values. This approach is particularly useful for assessing distortion in the dental arches. However, in order to obtain accurate results, a reference point in addition to the two measurement points is required. The three points can then be used to apply the Pythagorean theorem. A potential issue arises when the displacement overlaps with the direction of the distance measurement. Therefore, it is crucial to examine a point in all three dimensions to avoid potential inaccuracies in the calculations [22].

It is also possible to examine reference points designated in a specific cross-sectional plane of the samples in all directions of space, as well as to evaluate the marginal fit of the fabricated restoration. Several studies have already investigated the marginal fit of ceramic crowns, demonstrating that no significant differences were found between the marginal closure of restorations made with intraoral scanners and those created from conventional impressions [18].

1.3. The relevance of accuracy

Most patients are satisfied with their dental prosthesis if its shape, color, and function meet their expectations. However, beyond these aesthetic and functional aspects, one of the most critical factors for achieving a clinically acceptable, durable, and successful restoration is the accuracy of its internal fit and marginal adaptation [24,25]. Inadequate marginal fit can accelerate the dissolution of the cement and contribute to the development of microleakage, which may lead to the inflammation of the vital pulp. The greater the marginal discrepancy and the longer the cement is exposed to saliva, the faster the dissolution process occurs. Additionally, poor marginal adaptation promotes plaque retention and alters the subgingival microflora, increasing the risk of periodontal inflammation. In the case of implant-supported prostheses, inadequate fit can lead to both biological complications, such as mucositis and peri-implantitis, and mechanical issues, such as fracture of the prosthetic screw securing the suprastructure. Over time, these complications may result in implant failure and loss [26]. A precisely adapted restoration is a requirement for the success of a fixed dental prosthesis (FDP). The primary function of the cement is to occupy the space between the tooth surface and the restoration'surface, preventing displacement. Some studies found that a thinner cement layer may enhance the overall strength of the restoration [27]. The primary causes of these discrepancies are improper preparation and inaccurate impressions. To ensure the precise fit of the final prosthesis, it is essential to accurately reproduce the prepared tooth and surrounding soft tissues [22,28].

According to the literature, a marginal discrepancy ranging from 50 to 120 μm (or less) is considered clinically acceptable for fixed restorations, whereas values exceeding 200 μm are regarded as unacceptable [24,29,30]. There is no established agreement on the clinically acceptable accuracy range, though, in fixed restorations, the misfit that does not lead to biological complications is generally considered to be between 50 and 200 µm [31,32]. Most studies have adopted 120 µm as clinically acceptable, based on the original research by McLean and Fraunhofer [33].

1.4. Influencing factors of accuracy

Numerous factors influence the accuracy of digital impressions. According to the literature, scanning strategy—the sequence in which dental surfaces are digitized—plays a critical role, particularly in full-arch scans, where it has a significant impact on accuracy [34–37]. Research by Mennito et al. confirmed that scanning pathways significantly influence accuracy, particularly for extensive scans such as full arches [20]. Similarly, Ender et al. found that while scanning strategy does not significantly impact short-span segments, it becomes a determining factor in full-arch scans [38]. The scanning strategy recommended by the manufacturer was found to yield statistically superior accuracy compared to alternative approaches [39]. (Fig. 3.) As it is shown on the figure, scanning path A, the one recommended by the manufacturer, resulted in the most accurate impression.

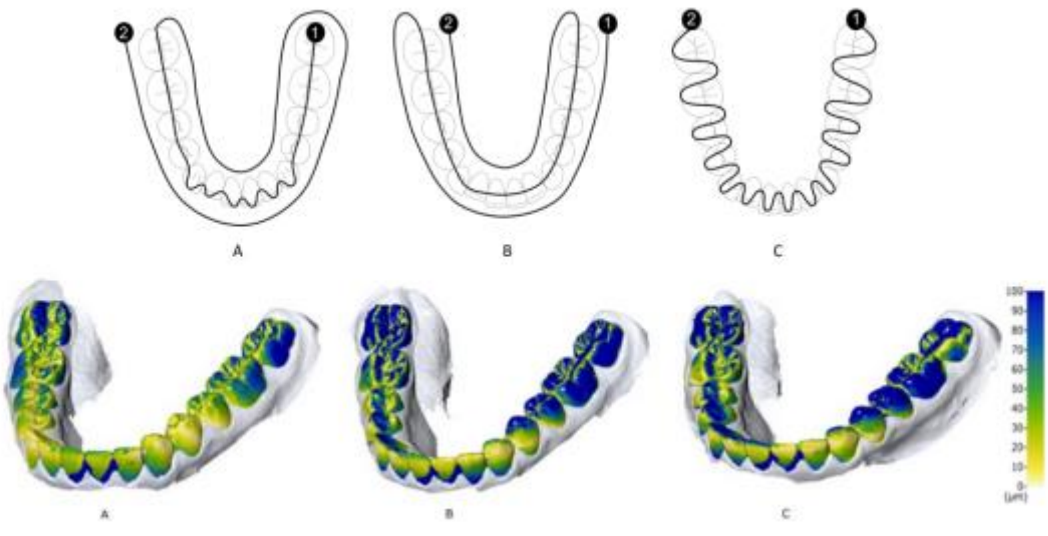

Figure 3: The effect of the scanning pattern on accuracy. The colour maps show the difference between the achieved accuracy by A, B and C scanning paths. [38].

Beyond scanning techniques, other factors also play a crucial role. The calibration of the IOS device directly influences accuracy and must be maintained regularly to ensure

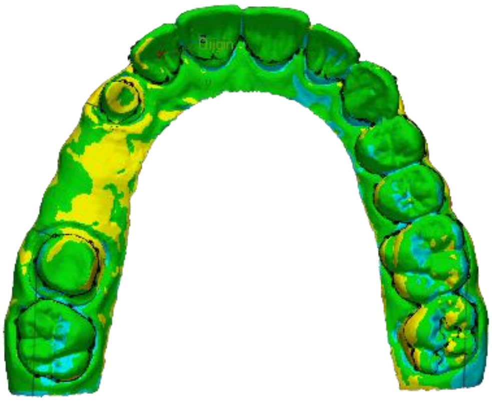

Figure 4: Colour coded map shows distortion at the edentulous part of the arch. Green colour indicates the 0–50 μm deviation, yellow means a positive distortion, while blue suggests a negative one.

optimal performance [40]. Additionally, ambient lighting conditions have been identified as a contributing factor affecting scanning precision [41]. Operator proficiency is another critical determinant, as the experience and skill level of the clinician performing the scan significantly impact the quality of the digital impression [42,43]. Given that digital impression-taking involves a learning curve, practitioners must gain sufficient experience with intraoral scanning before achieving confidence in routine clinical applications [44,45].

The presence of edentulous ridges further affects accuracy, as these areas lack distinct geometric features required for precise optical scanning [46]. (Fig. 4.) Therefore, scanning edentulous- or partially edentulous jaws (especially the lower jaw) or using them for implant retained restorations is controversial [34,47]. To enhance image acquisition and 3D anatomical scanning in edentulous patients, the use of artificial reference markers—such as adhesive landmarks, temporary anchorage device screws, or splinting systems—has been proposed [48]. However, their clinical usage can be complex and inconvenient. There are studies that suggest that, for all-on-X cases stereophotogrammetry (SPG) would be a more accurate alternative [49]. Pozzi et al. in 2022 investigated the accuracy of IOS versus stereophotogrammetry in case of complete arch digital impressions. They conclude that IOS had significantly higher extreme deviations compared to SPG [49].

Certain restorative and anatomical conditions also present challenges; for instance, reflections from metallic surfaces (such as restorations or orthodontic brackets), excessive saliva flow, and limited oral access (restricted mouth opening) can compromise image sharpness and resolution, ultimately reducing digital impression accuracy [50–52].

Previous studies have demonstrated that the accuracy of intraoral scanners (IOSs) decreases as the number of scanned teeth increases [53–55]. IOS has a limited field of view (FoV), due to this, a single-surface image is unable to capture all the surfaces of the teeth, not to mention the entire dental arch. These individual images have overlapping regions with adjacent surfaces. These overlapping regions are later integrated to create a unified 3D model of the whole tooth, which is then used to construct the full arch. Various methods and algorithms have been developed for the registration and stitching of these individual images. However, errors are inevitably introduced during this process, and these errors may accumulate as the scan progresses. This also can indicate that the number of images may affect accuracy, while the more images there are, the more alignments are required [22,56,57].

1.5. Hardware and software updates

A generation change occurs when a manufacturer enhances an existing intraoral scanner (previous generation) by upgrading both its hardware and software, resulting in a new version or next-generation model [5]. In contrast, a software update refers to a set of modifications aimed at fixing issues or improving the functionality of the software that operates the device. There is limited information in the literature regarding the influence of hardware and software components on the performance of intraoral scanners (IOSs) [58,59]. Manufacturers are constantly developing new generations of intraoral scanners, which include both updated hardware and new software versions. (Fig. 5.) These updates are designed to enhance the overall performance of the IOS, improving its ability to capture intraoral conditions more reliably, stably, and quickly. This not only facilitates the digitization process for the operator but also makes the procedure more comfortable for the patient. It is known that each new generation of intraoral scanners introduces advanced features—such as individual movement detection and denture workflows—

compared to their predecessors [10]. While numerous studies have examined the accuracy of intraoral scanners, few have specifically investigated the impact of software updates on accuracy. Previous studies in the literature have assessed the impact of various software features or updates on the accuracy of intraoral scanners. In 2020, Chiu et al. investigated the effect of a new software feature, high resolution, on the 3Shape Trios 3 IOS. The study found no significant difference in accuracy between the default resolution and the high-resolution setting. However, notable differences were observed in scanning time and the number of images or scans captured [59]. Vág et al. in 2021 also evaluated the impact of software updates on accuracy. They found statistically significant impact of software updates on the trueness and precision of various IOS systems. The updates inlfuenced accuracy in both positive and negative ways, it seems that the resulting variations remain within clinically acceptable limits [58].

Figure 5: The different generations of 3Shape Trios, Medit and Planmeca scanners [59]

1.6. Palate scanning

The use of intraoral scanning to capture partially and completely edentulous arches and design removable dentures using computer-aided design (CAD) software is becoming prevalent [61–63]. Soft tissue scanning, such as scanning the palate, generally exhibit lower accuracy compared to scans of tooth structures [64]. The palatine rugae are particularly important in the digital impression, as they have distinct textures within the oral cavity that help dental technicians align and merge different intraoral scans [64,65].

Figure 6: The palatinal rugae provides distinct geometric features for the IOS [65]

(Fig. 6.) However, making excellent scans of the palate can be difficult [67].

Literature suggests that intraoral scanners are capable of producing accurate 3D representations of the palate, although the accuracy of full arch scans involving the palate is influenced by the scanning strategy. Higher number of photograms captured during scanning though can lead to greater inaccuracy due to stitching errors [68]. This could mean that, including the palate in the digital impression may negatively affect the accuracy of the virtual model [69,70]. Inaccuracies tend to accumulate at the molars at the end of the dental arch, where the greatest reduction in accuracy is typically observed [64,71]. It can suggest that scanning the palate may help close the spatial mesh and enhance the overall accuracy of the scan. Thus, both the process of scanning the palate and the number of images captured during the scan may influence the accuracy of full arch scans.

2. Objectives

The thesis aimed to investigate different factors that can influence the accuracy of IOSs such as software and hardware updates, and palate scanning.

1. The first study aimed to investigate the effect of software updates on the accuracy in case of intraoral scanners with different software versions. The null hypothesis was that there is no association between the software version of the IOSs and the accuracy of digital impressions.
2. The second research intended to evaluate the effect of generation change on the accuracy and the inter-operator-reliability. The null hypothesis was that there is no significant difference between the accuracy of the old and new generation IOSs.
3. The third study aimed to assess the effect of the palate scanning in intraoral digital scans on the accuracy of complete arch scans. The null hypothesis was that the accuracy of complete arch scans is not influenced by scanning of the palatal area.

3. Methods

3.1. The impact of software updates on accuracy of intraoral scanners

The first study investigated two generations of intraoral scanners, using four different software versions as detailed in Table 1 [72]. The intraoral scanners under examination were the 3Shape Trios 3 (launched in 2015) configured with software version 18.1.2, which entered the dental market in 2018 (designated as TRI3_1), and software version 20.1.2, released in 2020 (designated as TRI3_2). Additionally, the 3Shape Trios 4 (introduced in 2019) was assessed with software version 19.2.2, also released in 2019 (designated as TRI4_1), and with software version 20.1.1, which was made available in 2020 (designated as TRI4_2). The Trios intraoral scanners utilize confocal laser scanning technology for the acquisition [73].

Table 1: The intraoral scanners used in the first study

	Generation	Software version
TRI3_1	3Shape Trios 3 Pod	18.1.2.
TRI3_2	3Shape Trios 3 Pod	20.1.2.
TRI4_1	3Shape Trios 4 Move	19.2.2.
TRI4_2	3Shape Trios 4 Pod	20.1.1.

Figure 7: The reference model used in the study [72].

A 3D printed polymethyl methacrylate (PMMA) model served as a reference model (NextDent 5100 3D printer - 3D Systems, Soesterberg, The Netherlands). (Fig. 7.) The model contained prepared teeth and edentulous region:

- 11 was supragingivally prepared for a crown
- 14 and 17 was supragingivally prepared for a bridge
- 15 and 16 were missing
- 26 was prepared for an inlay.

An experienced operator, who had over 5 years' experience, took 8 digital impressions with each IOS. The scanning strategy recommended by the manufacturer was followed. The starting point was the left prepared first molar's occlusal surface. After scanning the occlusal surface, the buccal and then the palatal surface was captured [63]. All the STL files were imported to the Geomagic Control X program (3D Systems, Rock Hill, SC, USA) and were compared to the reference STL file which was created by an industrial scanner (AICON SmartScan – 3D C5; AICON 3D Systems GmbH, Braunschweig, Germany) with the accuracy of 8 μm [74]. In the program, all files were first cleared from any unnecessary parts (meaning for example the palate and the tuber maxillae). This process was carried out by one operator.

During the comparison, fist an initial alignment was performed followed by best-fit-alignment and 3D comparison. The initial alignment matches the scan data's coordinate system to the nominal data and the best-fit-alignment finds the best overall alignment.

In this study, 3 parameters were measured:

1. parameter: a solo crown (11) accuracy
2. parameter: accuracy of a four-unit bridge containing an edentulous ridge

3. parameter: whole deviation of the complete arch representing the overall accuracy. (Fig. 8.)

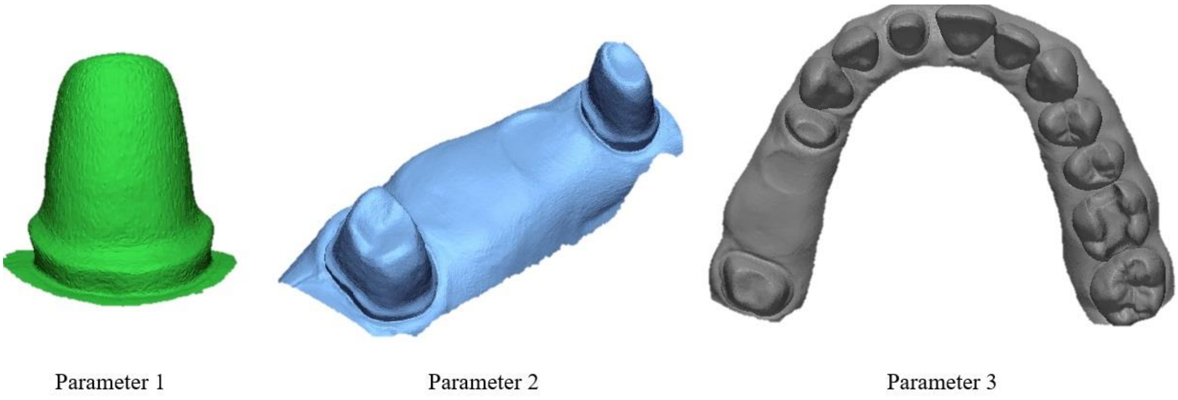

Figure 8: Measured parameters. Parameter 1 – solo crown, Parameter 2 – four-unit bridge, Parameter 3 – complete arch [72]

After the evaluation root mean square (RMS) data was exported from the software. Trueness was indicated by the arithmetic means of the RMS values and standard deviation (SD) was used for describing the precision [58]. Pairwise comparisons of device versions were conducted utilizing Student's two-sample t-test, contingent upon the fulfilment of normality assumptions. In instances where these assumptions were not met, the Wilcoxon rank-sum test was applied. Statistical analyses and data management were executed using the software package Stata.

3.2. The effect of generation change on the accuracy of full arch digital impressions

In the second study, altogether six IOSs were investigated as listed in Table 2 [75]. Two different generations of IOS from three different manufacturers were used. 3Shape intraoral scanners utilize confocal laser scanning technology, while Medit and Planmeca scanners employ the principle of triangulation combined with a video recording method to generate virtual models [73,76].

For Trios and Medit scanners, the primary distinction lay in their configurations: older models (Trios 3 and Medit i500) were wired, whereas newer versions (Trios 4 and Medit i700) feature wireless connectivity. Moreover, when the Trios 4 was initially launched, it included a specialized scanner tip for caries detection. However, following a software and hardware update, newly manufactured devices—including both Trios 4 and certain Trios 3 units—gained the ability to detect caries without requiring a dedicated tip [77].

In the case of Planmeca IOSs, the most significant differences between versions include tooth shade selection and caries detection capabilities [10,78]. These advanced features depend on the hardware architecture of the devices and become available only after corresponding hardware developments.

Table 2: The IOSs used in the second study

Manufacturer	**Hardware**	**Software**
3Shape	Trios 3	20.1.2.
3Shape	Trios 4	20.1.1.
Medit	i500	2.3.6.
Medit	i700	2.4.6.
Planmeca	Emerald	6.0.1.
Planmeca	Emerald S	6.0.1.

The reference model, used for creating the reference dataset, was the same which was used in the first study (Fig. 7).

Eighteen operators took part in this study using the six different IOS. 10-10-10 digital impressions were made with each scanner (30 altogether per IOS). Based on a previous study, this sample size was sufficient [58]. The participants were dental students with no experience in intraoral scanning. Before the scanning, they took part in a theoretical and a practical education. During the data collection process, the operators were supported by a supervisor with over five years of expertise in intraoral scanning. Prior to scanning, each device was calibrated in accordance with the manufacturer's guidelines [40].

During scanning, the operators followed the scanning path recommended by the manufacturer. In case of the Trios scanners the previously mentioned scanning strategy was applied. When using the Medit scanners, the scanning was initiated from the occlusal surface followed by the oral and then the vestibular side. The Planmeca scanners have a different strategy: the scanning was started from the occlusal surface in the molar region till the middle of the arch. After that, the oral and vestibular side was scanned. This same path was repeated on the opposite side[63]. (Fig. 9)

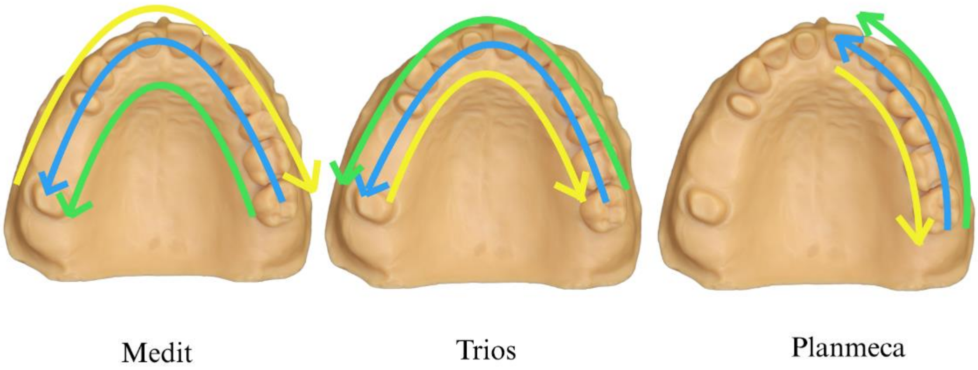

Figure 9: The recommended scanning sequence for each IOS (1st step – blue, 2nd step – yellow, 3rd step – green)

The STL files were subsequently imported into the Geomagic Control X software, where any extraneous structures (such as the maxillary tuberosity and the palate) were removed to standardize the datasets. The reference and experimental datasets were then aligned, and distortions were analyzed. Surface point deviations across the entire arch (WHL), as well as the distance between the distobuccal cusps of the second molars, were quantified. (Fig. 10.)

Surface point deviation and absolute arch distortion data were reported as medians and interquartile ranges (IQR) and visualized through box-whisker plots. To estimate the differences between new and older generations of intraoral scanners (IOS) for each brand, multilevel mixed-effects linear regression models were employed. Both outcome variables (surface deviation and arch distortion) were log-transformed to enhance normality. The model accounted for the non-independence of repeated measurements by the same operator and permitted heteroscedastic residuals across different IOS devices.

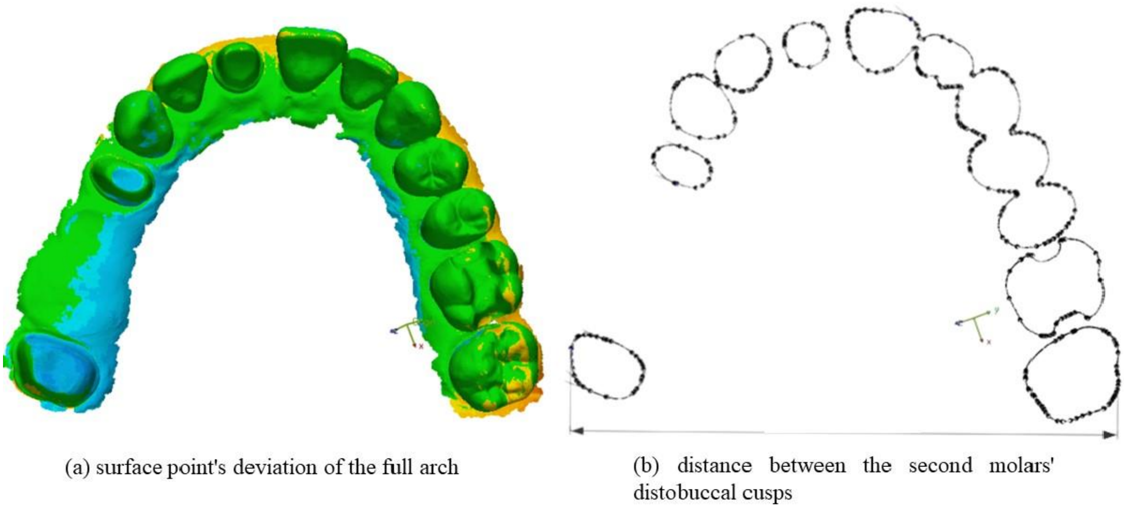

Figure 10: The measured parameters: a) surface point's deviation of the full arch b) distance measurement between the second molars' distobuccal cusps [75]

3.3. Evaluating the influence of palate scanning on the accuracy of complete-arch digital impressions–An in vitro study

A 3D printed completely dentate upper jaw model without restorations, or fixed dental prostheses, was fabricated (NextDent 5100 3D printer - 3D Systems, Soesterberg, The Netherlands) [79]. The material utilized was a light-cured, micro-filled hybrid (Model 2.0, NextDent, 3D Systems).

Figure 11: The digital impressions were created with (left) and without (right) the palate [79]

The operator was an experienced dentist with more than five years of experience. Altogether 40 digital impressions were taken, 20 without scanning the palate (NPAL), and 20 including the palate (PAL). (Fig.11.) Throughout the scanning process, the model was stabilized on a table, preventing any movement. A 3Shape Trios 5 intraoral scanner (Copenhagen, Denmark; software version 1.7.5.1) was used for scanning. All experiments were performed under consistent environmental conditions (approximately 1 atm pressure, 293 K (20°C), 0% humidity, and 1003 lx of illumination) [41]. The scanning path, mentioned in the previous studies, was used during scanning. An S-shaped scanning technique was utilized to capture the palatal surface and digitize the soft tissues (Fig. 12.) [63]. The scanning path consistently began at the right first molar. The scanning started on the occlusal surface of the right side moving to the left (blue line). The next surface was the buccal surface (red line), and then the palatal (green line). In case of the PAL scans, the palatal area was scanned in an S-shape.

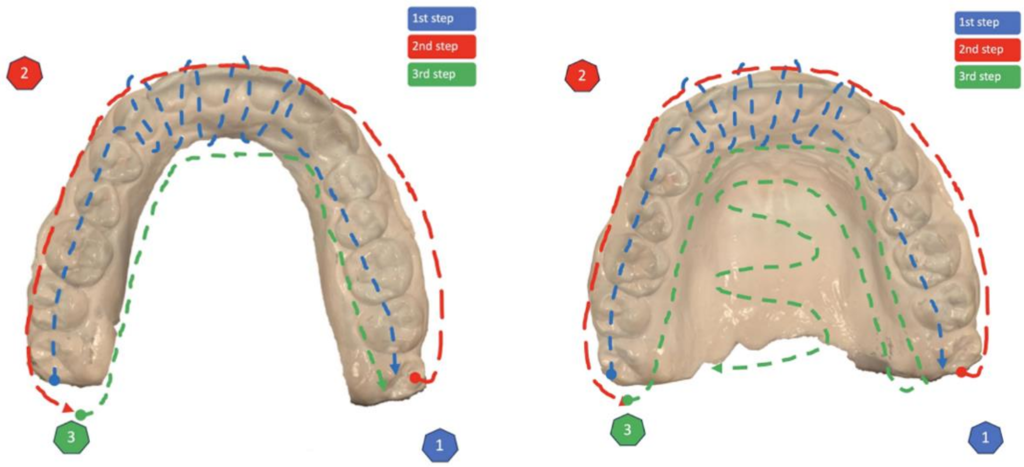

Figure 12: The scanning path used in the third study[79] .

The reference model was digitized using a 3Shape E3 laboratory scanner (3Shape Scanlt Dental 2.2.1.0, Copenhagen, Denmark) with an accuracy of 7 µm, which served to create the reference STL. The STL files generated by the IOS were imported into Geomagic Control X software and compared to the reference through a superimposition process (initial alignment and best-fit alignment). After aligning the files, a plane was defined intersecting the arch and 3 parameters were evaluated: right side (distance between the right first molar and the right incisor), left side (distance between the left first molar and the right incisor) and the arch distortion (distance between the right and left first molars). (Fig. 13.) During the scanning procedure, the total number of images generated by the intraoral scanner was registered.

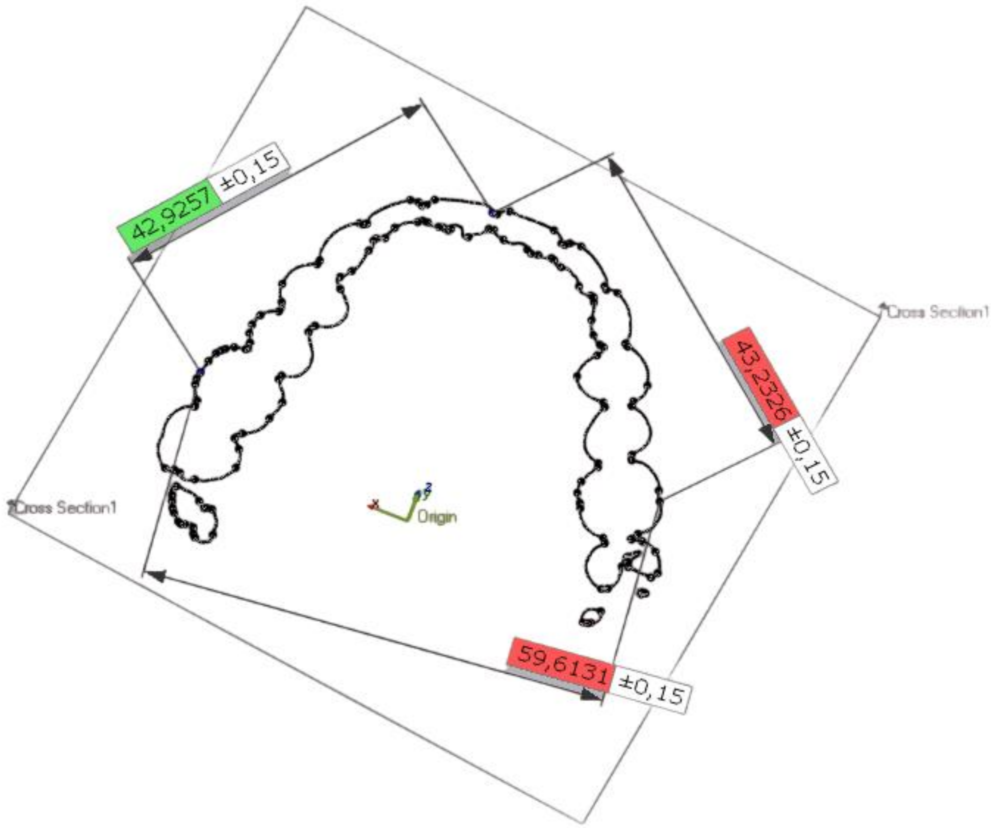

Figure 13: The measured parameters of the third study [79]

A total of 20 individual RMS data points were obtained for each parameter. Trueness was quantified as the mean ± standard deviation of the RMS values. Linear regression analysis was employed to compare the PAL and NPAL groups, as well as the right and left sides, with respect to absolute deviation.

4. Results

4.1. *The impact of software updates on accuracy of intraoral scanners*

- Accuracy results of Parameter 1:

  The accuracy results of the solo crown (11) were the following: TRI3_2 14.45 ± 0.36 µm, TRI3_1 13.26 ± 0.94 µm, TRI4_2 12.21 ± 0.71 µm and TRI4_1 11.75 ± 0.35 µm. Significant difference was found between TRI3_1 and TRI3_2. Between TRI4_1 and TRI4_2 no significant difference was measured. In this case the latest software version had the lowest accuracy result, but all data was under 20 µm, which is within the clinically acceptable accuracy range. (Fig. 14.)

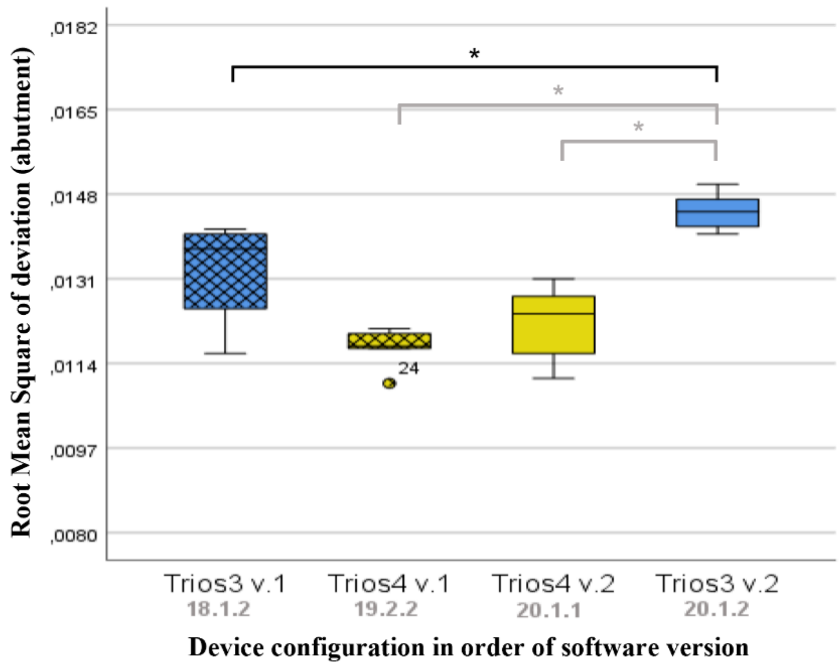

*Figure 14: Boxplot diagrams of the first parameter. Values are expressed in micrometers (µm). Significancy is showed by black * between same generations but different softwares and by grey * between generations. (* ≤ 0.005) [72]*

- Accuracy results of Parameter 2:

  The results for the four-unit bridge were as follows: TRI3_1 117.35 ± 20.11 µm, TRI3_2 45.86 ± 14.84 µm, TRI4_1 41.04 ± 16.48 µm, and TRI4_2 21.69 ± 7.50 µm. Statistically significant differences can be seen between most software versions and between the different generations as seen in Figure 15.

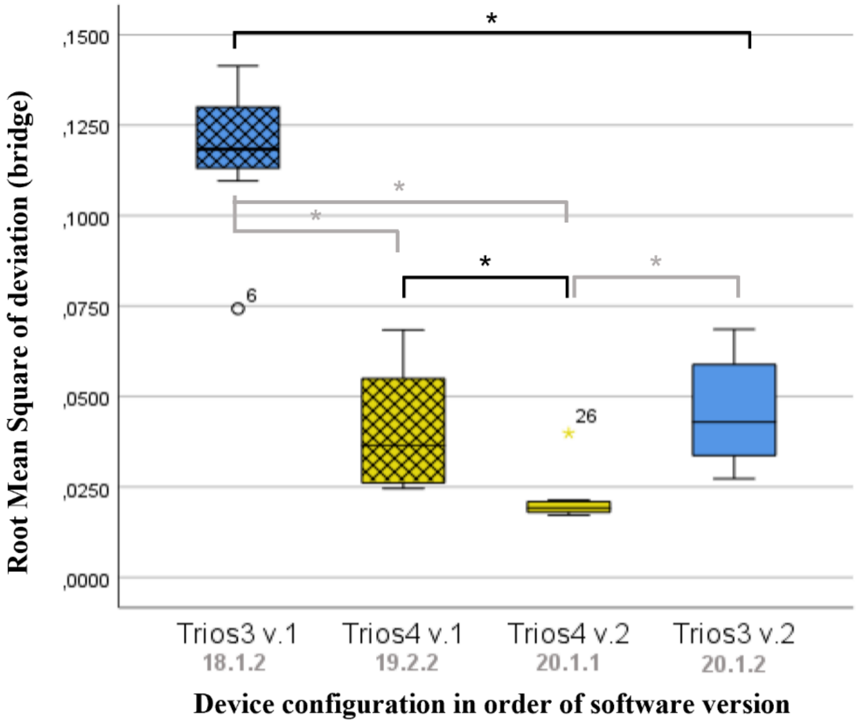

*Figure 15: Boxplot diagrams of the second parameter. Values are expressed in micrometers (µm). Significancy is showed by black * between same generations but different softwares and by grey * between generations. * ≤ 0.005 [72]*

- <u>Accuracy results of Parameter 3:</u>

  The results for the complete arch: TRI3_1 90.24 ± 15.35 µm, TRI4_1 52.91 ± 7.44 µm, TRI3_2 47.44 ± 9.17 µm, and TRI4_2 31.06 ± 5.24 µm. Regarding this parameter, the updated software had significantly higher accuracy in both generations. TRI3_2 (latest software) could not reach the level of TRI4_2 (second latest software). (Fig. 16.)

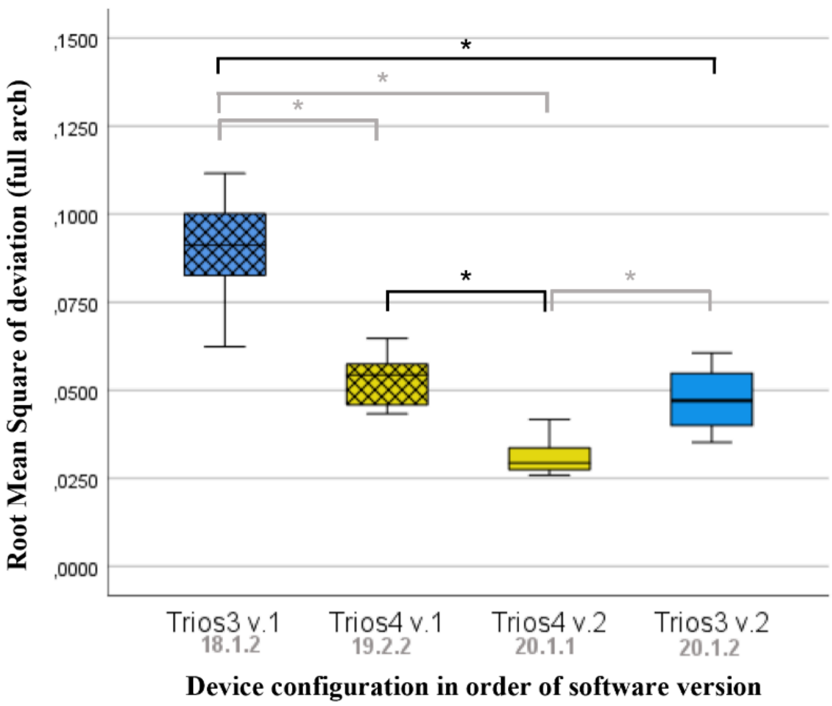

*Figure 16: Boxplot diagrams of the third parameter. Values are expressed in micrometers (µm). Significancy is showed by black * between same generations but different softwares and by grey * between generations. * ≤ 0.005 [72]*

4.2. The effect of generation change on the accuracy of full arch digital impressions

The results are reported as medians (IQR). Among the scanners assessed, the 3Shape Trios 4 exhibited the highest trueness for full-arch surface deviation, with a value of 34.0 ± 14.8 µm. Trueness values for the other intraoral scanners were the following: 3Shape Trios 3, 60.2 ± 25.3 µm; Medit i500, 54.4 ± 29.2 µm; Medit i700, 47.3 ± 21.7 µm; Planmeca Emerald, 112.8 ± 48.1 µm; and Planmeca Emerald S, 111.5 ± 29.0 µm. The Trios 4 demonstrated significantly improved accuracy compared to its predecessor, Trios 3. Similarly, the Medit i700 produced significantly more accurate impressions than the Medit i500. However, for the Planmeca scanners, the change in generation did not result in a notable difference in accuracy. (Fig 17. a) For arch distortion, the absolute values were used, yielding the following results: Trios 3 193.5 ± 160.2 µm; Trios 4 45.0 ± 103.9 µm; Medit i500 133.2 ± 184.1 µm; Medit i700 100.6 ± 127.8 µm; Planmeca Emerald

142.2 ± 241.1 µm; and Planmeca Emerald S 213.1 ± 283.6 µm. A significant improvement in accuracy was observed only between the 3Shape Trios generations, with

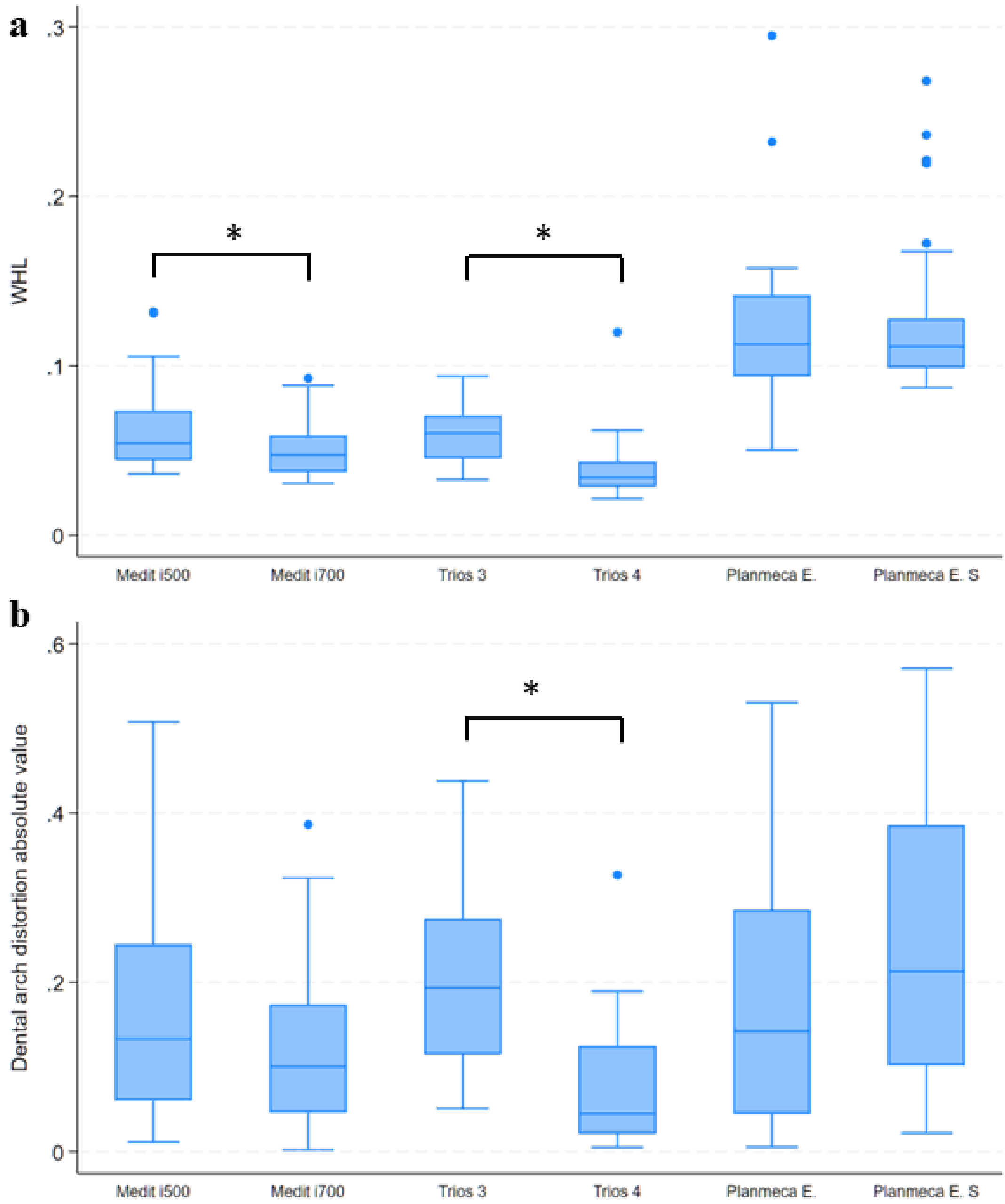

Figure 17: Boxplot diagrams of the results: a) surface point's deviation of the full arch b) distance measurement between the second molars' distobuccal cusps. [75]

Trios 4 showing a marked reduction in distortion compared to Trios 3. No significant differences in arch distortion were detected between the generations of Medit and Planmeca intraoral scanners. (Fig. 17. b)

In case of inter-operator reliability, no significant difference was found between the dental students in terms of accuracy. (Fig. 18.)

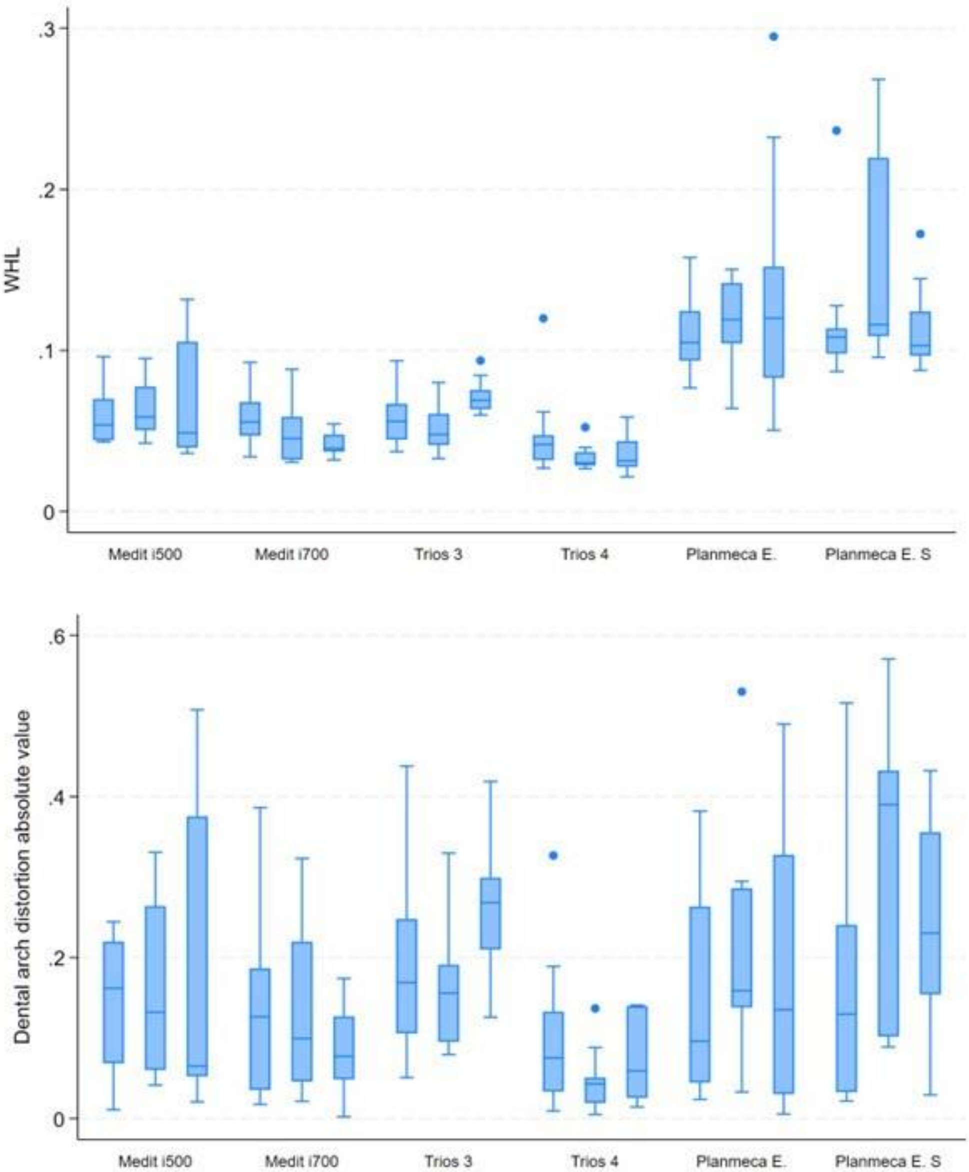

Figure 18: No significant difference was found regarding the inter-operator reliability [75]

4.3. Evaluating the influence of palate scanning on the accuracy of complete-arch digital impressions–An in vitro study

For the right side, no significant difference was found, and the trueness results were comparable: PAL 84 ± 45.6 µm, and NPAL 80.4 ± 40.4 µm. Also, for the left side, trueness results: PAL, 215.1 ± 70.2 µm, and NPAL, 233.9 ± 70.7 µm, though no significant difference was noted. However, scans on the right side were significantly more accurate than those on the left side in both PAL and NPAL cases. For the arch distortion, statistically significant difference was measured between the two groups of scans: PAL 135.3 ± 71.9 μm and NPAL 380.4 ± 255.1 μm. (Fig. 19.) The average number of images for PAL was 831.25 and for NPAL was 593.8. All measured data are shown in Table 3.

Table 3: The results of the third study

	Right side		Left side		Arch distortion	
	PAL	NPAL	PAL	NPAL	PAL	NPAL
1	-0,0644	-0,0413	-0,2429	-0,2995	-0,1689	-0,539
2	-0,0585	-0,088	-0,107	-0,2357	-0,067	-0,146
3	-0,0014	-0,1017	-0,0689	-0,253	0,0086	-0,1985
4	-0,0882	-0,0052	-0,2313	-0,191	-0,1258	-0,1026
5	-0,0176	-0,1091	-0,2399	-0,0912	-0,1243	0,0427
6	-0,005	-0,0957	-0,2934	-0,1436	-0,1047	-0,0364
7	-0,0636	-0,0907	-0,2412	-0,179	-0,1642	-0,1629
8	-0,1595	-0,0566	-0,1767	-0,346	-0,0918	-0,7355
9	-0,1066	-0,0683	-0,1748	-0,3438	-0,1524	-0,7402
10	-0,0862	-0,1163	-0,1266	-0,258	-0,1608	-0,3161
11	-0,0474	-0,0321	-0,2348	-0,1476	-0,2299	-0,1107
12	-0,1116	0,0123	-0,1613	-0,2788	-0,0391	-0,5095
13	-0,1027	-0,1005	-0,1831	-0,1542	-0,2423	-0,2645
14	0,0295	0,0084	-0,3061	-0,2026	0,0066	-0,1433
15	-0,0837	-0,1455	-0,2062	-0,2686	-0,1297	-0,4763
16	-0,0966	-0,0847	-0,2005	-0,2313	-0,1543	-0,2502
17	-0,0516	-0,0714	-0,3022	-0,2648	-0,2074	-0,5404
18	-0,1375	-0,0617	-0,1033	-0,2849	-0,0282	-0,5876
19	-0,0962	-0,0725	-0,1448	-0,1222	-0,0272	0,0204
20	-0,0618	-0,0706	-0,3206	-0,1635	-0,0891	0,1536

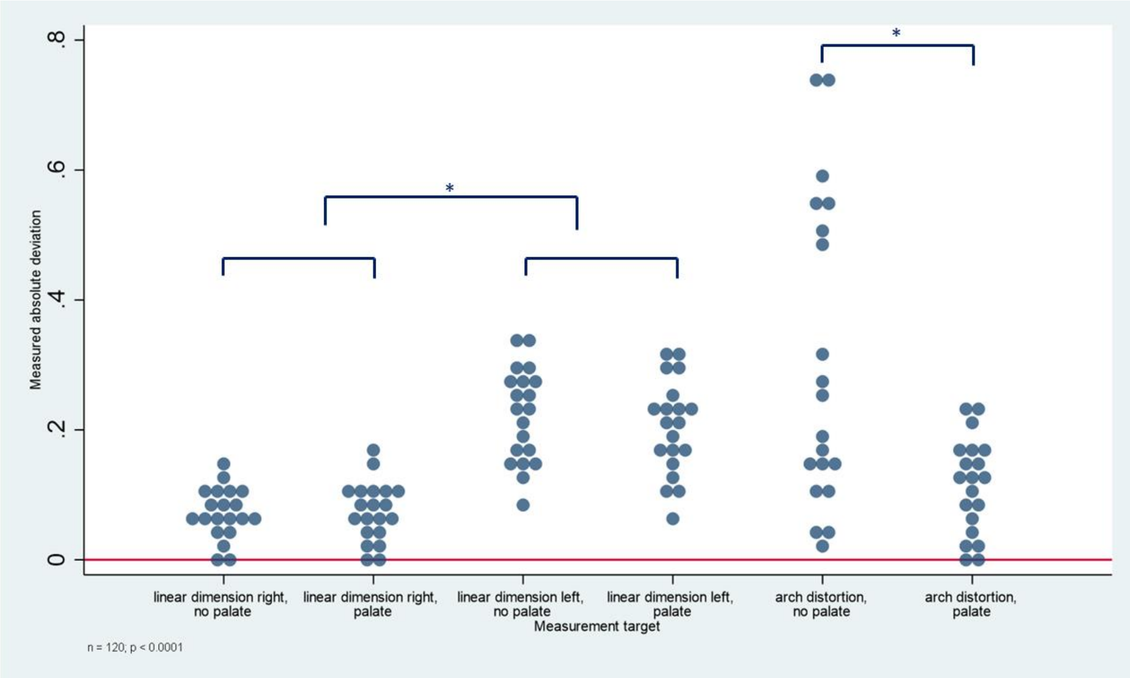

*Figure 19: The diagrams illustrate the absolute values of the measured parameters with and without palate scanning (Parameter 1 – right side, Parameter 2 – left side, Parameter 3 – arch distortion); *significance (p < 0.0001). Values are expressed in milimeters (mm). [79]*

5. Discussion

Numerous studies have examined various characteristics of IOSs, including scanning speed, ergonomic design, special features, and accuracy [3,42,80,81]. These in vitro studies specifically focused on evaluating the influencing factors of IOSs' accuracy.

5.1. The impact of software updates on accuracy of intraoral scanners

This study aimed to evaluate the impact of software updates on the accuracy of intraoral scanners. Two different generations of 3Shape scanners (Trios 3 and Trios 4) and four software versions were assessed in terms of trueness and precision.

The analysis of full-arch and bridge scan data led to the rejection of the null hypothesis of the first study, revealing a correlation between newer software versions and improved accuracy of digital impressions.

In terms of whole arch deviation, a significant improvement in both trueness and precision was observed. The Trios 3 scanner, operating with the latest software version (TRI3_2), demonstrated greater accuracy than the Trios 4 with an earlier software version (TRI4_1), despite the latter being a more recent generation of 3Shape device. Additionally, the updated Trios 4 scanner (TRI4_2) exhibited superior accuracy compared to the Trios 3 (TRI3_2).

Overall, the most precise results were obtained with the Trios 4 Pod running the updated software (TRI4_2), except for parameter 3, where the highest trueness was observed with the Trios 4 Pod using the older software version (TRI4_1). It is noteworthy that the software version used by the Trios 4 Pod in this study was not the latest available in the dental market. These findings suggest that both hardware and software components may influence IOS accuracy. This aligns with a study by Ender et al., which investigated the accuracy of full-arch and posterior scans using two software versions of the CEREC Omnicam. Their results demonstrated improved accuracy with the updated software version across both parameters [38].

For parameter 2, significant differences were observed between the results obtained using the TRI3_1 and the TRI3_2, meaning the software update enhanced the accuracy. The data for parameter 2 demonstrated an improvement in both trueness and precision compared to parameter 3, which measured the surface deviation of the prepared incisor.

The presence of an edentulous ridge between teeth 14 and 17 was a key aspect of this parameter, as most intraoral scanners exhibit reduced accuracy when scanning edentulous areas. Since edentulous regions provide less geometric information than tooth surfaces, IOS devices face greater challenges in stitching images accurately [82,83]. Moreover, the size of the edentulous region can affect the recognition of overlaps, thereby influencing accuracy [38].

Kim et al. evaluated the accuracy of IOS devices on edentulous ridges. They used a 3Shape Trios 3, reporting an average accuracy of 36.1±13.0 μm. In our study, the Trios 4 scanner with software version 19.2.2 (TRI4_1) demonstrated a comparable accuracy of 41.04±16.48 μm [46]. However, the Trios 4 scanner with the updated software version (TRI4_2) yielded superior results in both trueness and precision, with an accuracy of 21.69±7.50 μm. The differences between our findings and those of Kim et al. may be attributed to the shorter edentulous span examined in our study.

For the solo crown, a negative effect of software updates was observed on trueness. However, the difference across the scanner configurations was less than 5 μm, making the clinical significance of this difference negligible. Our study yielded more accurate results than those reported in the literature. Park et al. investigated the accuracy of the 3Shape Trios 3 in 2016, reporting an accuracy of 49.7±13.0 μm for a single crown on the first incisor [84]. In contrast, our findings showed greater accuracy: TRI3_2 (14.45±0.36 μm) and TRI3_1 (13.26±0.94 μm). In our study, two software versions of the Trios 3 scanner were evaluated: version 18.1.2, released in 2018, and version 20.1.2, introduced in 2020. Park et al.'s research was conducted in 2016, meaning the Trios 3 scanner used in their study operated on an older software version, which may explain the differences in accuracy.

Zimmerman et al. investigated the accuracy of prepared teeth for single-unit restorations using the CEREC Omnicam with two software versions (4.6.1 and 5.0.0). Their study found no significant difference in accuracy between the two versions (36.7 μm for version 4.6.1 and 40.5 μm for version 5.0.0) [85]. Similarly, our results indicate that intraoral scanners running older software versions produced accuracy levels comparable to those with updated software.

Discrepancies between our findings and those in the literature may also stem from variations in the geometry of the prepared abutment and its proximity to adjacent teeth, which influence the scanner's field of vision and overall accuracy. Since each measured object has a unique shape, direct comparisons between studies remain challenging [86,87].

This study has certain limitations. As our results are based on model scanning,conducted in an in vitro setting, further research is needed to evaluate these parameters under clinical conditions. Multiple factors can influence the accuracy of intraoral scanners in clinical environment, including saliva flow rate, patient-specific anatomical characteristics, and the operator's proficiency in digital impression-taking.

Additionally, this study focused on only two intraoral scanners from the same manufacturer, both of which utilize confocal laser technology and capture data through a video sequence [26]. Given the variety of intraoral scanners employing different data acquisition methods, the findings may not be universally applicable. Future research should explore a broader range of intraoral scanning devices to assess the impact of software updates across different technologies.

5.2. The effect of generation change on the accuracy of full arch digital impressions

Software updates and new IOS generations are generally expected to enhance performance, particularly the accuarcy. However, our findings suggest that not all newly released IOS generations meet these expectations, therefore the null hypothesis has to be rejected. In this study, we evaluated the accuracy of six intraoral scanners from three manufacturers: 3Shape Trios 3 (20.1.2) and Trios 4 (20.1.1), Medit i500 (2.3.6) and i700 (2.4.6), and Planmeca Emerald (6.0.1) and Emerald S (6.0.1).

Trios 3 was launched in 2015, the Medit i500 was presented in 2018 and the Planmeca Emerald in 2017 [3,5]. Michelinakis et al. assessed the accuracy of complete-arch scans using the Trios 3 (1.6.9.1), Medit i500 (2.3.0), and Planmeca Emerald (5.3.2.13). Their findings reported trueness values of 16.8±3.8 µm for Trios 3, 15.8±5.9 µm for Medit i500, and 56.5±15.2 µm for Planmeca Emerald [88]. While there are some variations between their results and our measurements, the ranking of scanner accuracy remained consistent: Medit i500 demonstrated superior trueness compared to Trios 3, while Planmeca Emerald exhibited the lowest accuracy.

In 2021, Nulty evaluated the accuracy of complete-arch digital impressions. Trios 3, Trios 4 and Medit i500 were also investigated among the 9 scanners they used in the study. Their findings showed that Trios 4 (20.8±6.2 μm) had higher accuracy than Trios 3 (27.7±6.8 μm), which aligns with our study's results [89]. However, discrepancies between our study and those by Michelinakis et al. and Nulty may stem from differences in reference models. Unlike our study, their models lacked edentulous ridges or prepared teeth, which can negatively affect scanning accuracy, as previously discussed.

Further supporting the impact of generational advancements, Park et al. in 2019 evaluated Trios 2 and Trios 3, concluding that the newer Trios 3 scanner outperformed its predecessor in full-arch accuracy [56]. Similarly, in 2022, Ochoa-López et al. investigated the Medit i500 and i700 scanners, finding that the newer Medit i700 demonstrated slightly improved accuracy [90]. These findings, consistent with our results, suggest that newer generations of IOS devices generally enhance scanning accuracy.

Beyond hardware and software improvements, IOS accuracy is also influenced by operator proficiency [34]. Inexperienced dental students may perform less accurate digital impressions, than experienced dentists. However, in our study, no significant differences were observed in the accuracy of virtual models produced by different student operators. This suggests that digital impression technology offers a more accessible, reliable, and less technique-sensitive alternative to conventional impression-taking, making it particularly beneficial for dental education. Kamimura et al. reported in 2017 that digital impression-taking had superior reproducibility than traditional methods and was not significantly affected by operator experience [91]. These findings indicate that IOSs may be less technique-sensitive than conventional impression techniques.

Future research should further explore whether there are significant differences in intraoral scanning accuracy between experienced professionals and novice users. Additionally, comparisons between conventional and digital impression techniques across different skill levels could provide valuable insights into the learning curve and overall effectiveness of digital workflows in clinical practice.

This study has several limitations that should be acknowledged. As an in vitro study, the experimental conditions were more controlled and ideal compared to a real clinical setting, where factors such as saliva, presence of the tongue, and patient head movement can negatively affect the accuracy of digital impressions. Additionally, the operators were dental students with no prior experience using intraoral scanners. Furthermore, future research should explore accuracy using different types of models, including edentulous models and cases of crowded dentition. This study assessed IOSs from only three manufacturers, highlighting the need for further evaluation of a broader range of IOS devices.

5.3. Evaluating the influence of palate scanning on the accuracy of complete-arch digital impressions–An in vitro study

According to this study's results, the null hypothesis was rejected. The findings propose that including the palatal region in the digital impression significantly enhances the accuracy of complete arch scans. However, regarding the number of images acquired, definitive conclusions could not be concluded from the current data, necessitating further investigation. Operator experience and the scanning strategy can influence scanning accuracy [10,45,92]. The number of images in a scan may reflect the operator's expertise; improper execution of the scanning procedure or abrupt hand movements during digitization may induce distortions. In such cases, the intraoral scanner compensates by capturing additional images to ensure proper imaging [93,94].

Limited information is available regarding the effect of palatal scanning and image number on IOSs' accuracy. The third study investigated the impact of incorporating the palate into scans. The number of images were also recorded during scanning to evaluate the effect on accuarcy. A dentist with experience in intraoral scanning performed 40 digital impressions, 20 including the palate (PAL) and 20 without including it (NPAL). The exported STL files were then imported into the Geomagic Control X software (3D Systems, Rock Hill, SC, USA) for accuracy assessment. Analysis of the right side of the digital impressions revealed that trueness values between PAL and NPAL cases were comparable, with no statistically significant difference observed. However, the right side of the STL files exhibited significantly greater accuracy than the left side regardless of the palate inclusion. The reason behind this is, that the scanning was initiated from the right side and continued to the left. Due to stitching errors it leaded to greater inaccuracies on the left side [94].

In case of the left side, we did not found significant difference regarding PAL and NPAL digital impressions. Although, a significant difference was noted in case of arch distortion, with PAL scans exhibiting reduced distortion. These findings suggest that incorporating the palate into intraoral scans enhances the digital impression's accuracy by ensuring a closed spatial mesh. However, this finding cannot be extrapolated to the lower jaw, as there is no analogous anatomical structure connecting the left and right mandibular segments. Few studies have specifically examined the effects of palatal incorporation on IOS accuracy. Mizumoto et al. in 2019 investigated the impact of palatal scanning on IOS accuracy, concluding that virtual model accuracy remained consistent regardless of whether the palatal soft tissue was stitched [95]. Direct comparison with the above-mentioned study is limited due to differences in the models used, as they used an edentulous dental model. Another study investigated the relationship between palate morphology and scan accuracy, reporting that a more concave palate diminished accuracy, though they did not found significant differences [96]. Akl et al. evaluated the impact of palatal scanning on the accuracy of virtual upper jaw models using three different IOSs in 2023, concluding that palatal inclusion improved trueness regardless of the IOS type [97]. Conversely, some studies suggest that excluding the palate enhances accuracy, arguing that regions with low information content, such as the palate, may introduce informational noise [98,99].

The findings of the third study indicate that including the palatal region during scanning significantly improves the accuracy of full arch scans. Additionally, the number of images captured during the scanning process was examined. Although literature suggests a potential correlation between image count and accuracy, this relationship has not been definitively established [42,94,100,101]. In the present study, PAL STL files contained a greater number of images, yet their overall accuracy exceeded that of NPAL models. This contradicts previous suggestions that increased image overlaps may reduce virtual model accuracy [69,70]. Other studies have found no correlation between total discrepancy and image count recorded by IOS parameters [59]. Based on these findings, a definitive conclusion regarding the effect of image count on scan accuracy remains elusive, necessitating further investigation. Future studies should explore the influence of palatal morphology on accuracy and consider incorporating additional IOSs to assess accuracy in relation to palatal scanning.

This study has several limitations. First, it did not assess the influence of different palatal morphologies and geometries, such as gothic palate, on scan accuracy. Only a one reference model was scanned, which may have impacted the results (e.g., the presence of an edentulous ridge). Second, only one intraoral scanner was evaluated, and the findings may not be generalizable to other IOSs due to variations in mapping principles. Additionally, this was an in vitro study and the exclusion of clinical factors such as saliva, blood, restricted intraoral space, and soft tissue movement, all of which affects scanning accuracy.

6. Conclusions

1. Advancements in intraoral scanner software can significantly enhance trueness and precision, particularly in full-arch scanning. The edentulous region may still negatively impact accuracy; though, software updates appear to enhance the accuracy of digital impressions.
2. Advancements in intraoral scanner (IOS) technology influence the accuracy of surface digitalization. For Trios scanners, newer generations demonstrate a clear improvement in digital impression accuracy compared to earlier versions. In contrast, Medit scanners show only a slight enhancement in accuracy with generational advancements, while no significant differences were observed for Planmeca scanners.
3. Digital impression-taking proved to be operator-independent in case of dental students.
4. Incorporating palatal scanning may contribute to closing the spatial mesh, thereby significantly improving the accuracy of dental scans.

7. Summary

The increasing integration of digital workflows in dentistry, including intraoral scanning, has significantly improved efficiency and reproducibility in both clinical and laboratory settings. While intraoral scanners (IOSs) have demonstrated accuracy comparable to conventional impression techniques for short-span impressions, discrepancies have been observed in full-arch digital impressions. Given that digital impression accuracy is crucial for the long-term clinical success of definitive restorations, optimizing IOS technology remains a key focus in modern prosthodontics and restorative dentistry.

This doctoral thesis investigates various factors influencing IOS accuracy, including software updates, generational advancements in scanner hardware, and the impact of palatal scanning. Three distinct studies were conducted to examine these variables.

The first study aimed to assess the effect of software updates on IOS accuracy by comparing digital impressions obtained using different software versions. The second study evaluated the impact of generational changes on the accuracy of different IOSs. The third study investigated the effect of palatal scanning on the accuracy of complete arch scans.

Within the limitations of these studies, the research highlights the importance of continuous advancements in both IOS hardware and software in improving digital impression accuracy. Software updates play a crucial role in enhancing trueness, particularly in full-arch scanning, while generational improvements in scanner technology can lead to varying degrees of accuracy enhancement depending on the manufacturer. Additionally, palatal scanning has been identified as a factor that can improve digital impression accuracy by optimizing spatial mesh closure. However, further investigations are needed to better understand the relationship between image count and scan accuracy, as well as the influence of palatal morphology on digital impressions.

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9. Bibliography of the candidate's publications

9.1. Publications related to the thesis

- Schmalzl, J., Róth, I., Borbély, J. Hermann P, Vecsei B. The impact of software updates on accuracy of intraoral scanners. *BMC Oral Health* **23**, 219 (2023). https://doi.org/10.1186/s12903-023-02926-y
- Schmalzl, J., Róth, I., Borbély, J., Hermann P, Vecsei B. The effect of generation change on the accuracy of full arch digital impressions. *BMC Oral Health* **23**, 766 (2023). https://doi.org/10.1186/s12903-023-03476-z
- Schmalzl J, Keskeny GyÁ, Hermann P, Pál A, Géczi Z, Borbély J, Róth I. Evaluating the influence of palate scanning on the accuracy of complete-arch digital impressions-An in vitro study. J Dent. 2024 Apr 20;145:105014. doi: 10.1016/j.jdent.2024.105014. Epub ahead of print. PMID: 38648874.

9.2. Publications not related to the thesis

- Schmalzl J., HermannP., & AmbrusS. (2023). Krónikus reumatológiai kórképpel rendelkező páciens protetikai ellátása. Fogorvosi Szemle, 116(3), 136-142. https://doi.org/10.33891/FSZ.116.3.136-142
- Róth I, Géczi Z, Végh DC, Hegedüs T, Pál A, Hermann P, et al. The role of artificial intelligence in intraoral scanning for complete-arch digital impressions: An in vitro study. Journal of Dentistry 2025;156. https://doi.org/10.1016/j.jdent.2025.105717

10. Acknowledgements

I would like to express my sincere gratitude to Prof. Dr. Péter Hermann for making it possible to carry out the research and investigations. My deepest appreciation also goes to my supervisors, Dr. Judit Borbély and Dr. Bálint Vecsei, for their invaluable guidance and continuous support throughout this journey.

I am also grateful to the members of the Digital Research Group for their contributions, as well as to my co-authors for their collaboration namely Dr. Ivett Róth, Dr. Adrienn Pál, Dr. György Keskeny and Dr. Zoltán Géczi.

Finally, I extend my heartfelt thanks to my family and friends for their unwavering encouragement and support, which have been essential in completing this work.