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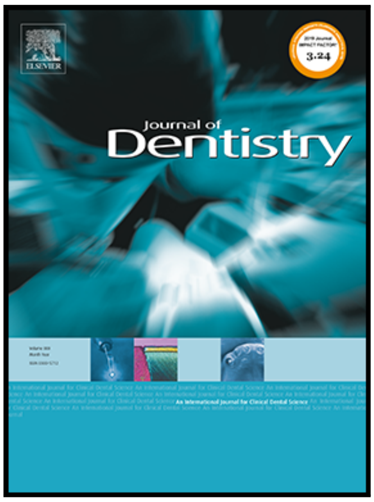

Comparison of intraoral and laboratory scanners to an industrial-grade scanner while analyzing the fabrication trueness of polymer and titanium complete-arch implant-supported frameworks

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Original article

Full Title: Comparison of intraoral and laboratory scanners to an industrial-grade scanner while analyzing the fabrication trueness of polymer and titanium complete-arch implant-supported frameworks

Short title: Trueness of different scanners for digital deviation analyses

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ABSTRACT

Objectives: To compare the scans of different intraoral scanners (IOSs) and laboratory scanners (LBSs) to those of an industrial-grade optical scanner by measuring deviations of complete-arch implant-supported frameworks from their virtual design file.

Material and methods: Ten polyetheretherketone (PEEK) and 10 titanium (Ti) complete-arch implant-supported frameworks were milled from a master standard tessellation language (STL) file. An industrial-grade blue light scanner (AT), 2 LBSs (MT and E4), and 3 IOSs (PS, T3, and T4) were used to generate STL files of these frameworks. All STLs were imported into an analysis software (Geomagic Control X) and overall root mean square (RMS) values were calculated. Marginal surfaces of all STL files were then virtually isolated (Medit Link v

2.4.4) and marginal RMS values were calculated. Deviations in scans of tested scanners were compared with those in scans of AT by using a linear mixed effects model (α=.05).

Results: When the scans of PEEK frameworks were considered, PS and T3 had similar overall RMS to those of AT ($p \geq .076$). However, E4 and T4 had higher and MT had lower overall RMS than AT ($p \leq .002$) with a maximum estimated mean difference of 13.41 µm. When the scans of Ti frameworks were considered, AT had significantly lower overall RMS than tested scanners ($p \leq .010$) with a maximum estimated mean difference of 31.35 µm. Scans of tested scanners led to significantly higher marginal RMS than scans of AT ($p \leq .006$) with a maximum estimated mean difference of 53.90 µm for PEEK and 40.50 µm for Ti frameworks.

Conclusion: Only the PEEK framework scans of PS and T3 led to similar overall deviations to those of AT. However, scans of all tested scanners resulted in higher marginal deviations than those of AT scans.

Clinical Significance: Scans performed by using PS and T3 may be alternatives to those of tested reference industrial scanner AT, for the overall fabrication trueness analysis of complete-arch implant-supported PEEK frameworks.

1. INTRODUCTION

The fabrication of implant-supported fixed prostheses has shifted from conventional to digital, as error prone laboratory steps could be eliminated with the integration of computer-aided design and computer-aided manufacturing (CAD-CAM) in dentistry. Additive or subtractive manufacturing technologies enable the fabrication of metal-based, ceramic-based, and polymer-based prosthesis frameworks [1]. Titanium (Ti) has been the material of choice for complete-arch implant-supported frameworks with its reported acceptable fit [2, 3], while resin-based materials have been proposed as alternatives to metal frameworks [4]. However, there are many unknowns about the applicability of recently introduced polymer-based materials in complete-arch implant situations; their fabrication trueness and prosthetic fit are not well-known.

Accuracy is a combination of trueness, which is the closeness between the measured data and the reference data, and precision, which is the closeness between repeated measurements [5]. Digital analysis technologies have enabled the fabrication trueness analysis of prosthetic components. A mesh is obtained through the scans of the component and 3D deviation analyses can be done by using software programs, superimposing this mesh data over CAD file to evaluate how much the fabricated prosthesis deviated from the CAD data [6-8]. Digital analyses can be performed regardless of the mesh file source and the advancements in digital technologies have also facilitated the use of various scanners to generate these meshes [9]. Industrial-grade scanners are used in dental research to generate reliable reference scans of models, scan bodies, and various types of dental prostheses [10-13]. However, industrial-grade scanners can be difficult to access for dental professionals. Intraoral scanners (IOSs) and laboratory scanners (LBSs) can also be used to generate digital images and they are commonly used in daily practice as they have become affordable in recent years. IOSs capture 3-dimensional (3D) information intraorally or extraorally, and LBSs acquire this 3D information by scanning impressions, models, or a dental product [10, 14, 15]. LBSs are generally preferred for long-span or complete-arch situations as they have a large area of view and no linear stitching issues [16, 17]. IOSs are convenient to use and enable improved line of sight as their wands can be rotated manually to the desired position, which allows the finalization of an object’s scan in one round. They also can provide predictable scans not only for short-span [10, 14, 18], but also for complete-arch situations [19-21]. Therefore, IOSs and LBSs may be able to compete with industrial-grade scanners for dental research scans. Such a possibility would enable researchers to use readily available equipment for fabrication trueness analysis without being limited to costly industrial-grade scanners. In addition, dental technicians and clinicians can benefit from knowing the fabrication trueness of newly manufactured prostheses, even before the clinical appointment, by scanning them with their intraoral or laboratory scanners and analyzing deviations from the CAD file.

To the authors' knowledge, no study has focused on scan trueness of IOSs and LBSs when compared with an industrial-grade scanner. A study based on this comparison by focusing on fabrication trueness of metal-based and polymer-based implant-supported complete-arch frameworks would broaden the knowledge on the possibility of using IOSs or LBSs as reference scanners in future studies, and in laboratories and clinics for fabrication trueness evaluation, such as quality control. Therefore, the present study aimed to compare the scans of 3 IOSs and 2 LBSs to those of an industrial-grade blue light optical scanner (ATOS Core 80 5MP; GOM GmbH, Braunschweig, Germany) by measuring the deviations of polyetheretherketone (PEEK) and Ti complete-arch implant-supported frameworks from their CAD file. The first null hypothesis was that there would be no difference between tested scanners and the industrial-grade optical scanner scans when overall deviations of the frameworks were considered, and the second null hypothesis was that there would be no difference between tested scanners and the industrial-grade optical scanner when marginal deviations of the frameworks were concerned.

2. MATERIAL AND METHODS

Figure 1 shows the overview of the present study. The present study followed the methodology of previous studies for the fabrication of screw-retained complete-arch implant-supported frameworks [3, 4, 13, 22, 23]. A maxillary typodont model with 4 implants (2 straight and 2 distally tilted, Nobel Active RP 4.3 × 13 mm; Nobel Biocare AG, Zürich, Switzerland) located at right first molar, right canine, left canine, and left first molar sites

(Fig. 2) was digitized by using an LBS (S600 ARTI; Zirkonzahn GmbH, Gais, Italy) to design a 12-unit complete-arch framework master standard tessellation language (M-STL) file. M-STL was used to subtractively manufacture 10 titanium (Ti, rematitan blank Ti5; Dentauraum GmbH & CoKG, Ispringen, Germany) and 10 polyetheretherketone (PEEK, BioHPP; bredent GmbH, Senden, Germany) frameworks by using a 5-axis milling unit (Coritec 550i; Imes-Icore GmbH, Eiterfeld, Germany) in line with each material's manufacturer's recommended milling burs and strategies. An experienced dental technician performed all post-processing procedures to separate the frameworks from disks and carefully remove any residues at the abutment interfaces. Ten frameworks from each material was fabricated to standardize and minimize the possible effect of fabrication process on measured deviations.

An industrial-grade blue light optical scanner (AT, ATOS Core 80 5MP; GOM GmbH, Braunschweig, Germany), 2 LBSs (MT, T710; Medit, Seoul, Korea and E4, E4 Dental Scanner; 3Shape, Copenhagen, Denmark), and 3 IOSs (PS, CEREC Pimescan; Dentsply Sirona, Bensheim, Germany, T3, TRIOS 3 and T4, TRIOS 4; 3Shape, Copenhagen, Denmark) were used for digitizing all frameworks and generating test scan STLs (TSTLs) (Table 1). An anti-reflective spray (Dr. MAT DENTAL; MAT Kimya, İstanbul, Turkey) was applied onto Ti frameworks to facilitate scanning and all scans were performed in the same temperature- (20 °C) and humidity-controlled (45%) room that was lit by sunlight [24]. PS scans started by capturing the lingual surfaces, followed by occlusal and buccal surfaces, while T3 and T4 scans started by capturing the occlusal surfaces, followed by lingual and buccal surfaces [25]. In addition, soft-tissue surface of the frameworks was scanned after prepared tooth region scans for all tested scanners and a single operator (D.Ö.D) performed the scan of each framework once with each scanner. All STL files were imported into a metrology-grade 3-dimensional (3D) analysis software (Geomagic Control X v.2018.1.1; 3D Systems, Morrisville, NC, USA) and the root mean square (RMS) method was used to calculate deviations. For overall RMS measurements, TSTLs were superimposed over M-STL by using N-points alignment tool (one point located at the palatal aspect between the right second premolar and first molar, one point located at the tip of the interdental papilla between central incisors, and one point located at the palatal aspect between the left premolars) and best fit alignment function of the software. For marginal RMS measurements, all STL files were first imported into another software (Medit Link v 2.4.4; Medit, Seoul, Korea) and marginal surfaces were virtually isolated (MM-STL for the margins of M-STL and MTSTL for the margins of TSTLs). These new STL files were then imported into the same metrology grade software and TSTLs were superimposed over the MM-STL by using the same methodology. For the initial N points alignment, one point was selected at the lower border of each abutment interface other than the one located at the left canine site (Fig. 3). For both overall and marginal RMS values, color maps (Figs. 4 and 5) were generated by using the 3D compare tool of the software. The maximum and minimum deviation values were set at +100 µm and −100 µm with a tolerance range of +10 µm and −10 µm [26] and the software automatically calculated the overall RMS values and mean marginal RMS values of the 4 isolated marginal surfaces.

A linear mixed effects model with a random intercept for the number of the specimen was used to compare the deviations in scans from each scanner with the deviations in reference scanner (AT) scans within each surface-material pair. A linear mixed effects model with random intercept was chosen since correlation may exist between the scanned RMS values from different scanners on the same framework. A statistical software program (R v3.6.1; R Core Team 2021, Vienna, Austria) was used for the analyses (α=.05).

3. RESULTS

Figure 6 illustrates the box-plot graphs of overall RMS and Figure 7 illustrates box-plot graphs of marginal RMS of each scanner within each framework material. When PEEK framework scans were considered, PS (*p*=.181) and T3 (*p*=.076) scans led to similar overall RMS to those of the scans of AT. However, scans of MT led to lower (*p*=.002) and those of E4 (*p*<.001) and T4 (*p*<.001) led to higher overall RMS than the scans of AT. When Ti framework scans were considered, scans of all scanners led to higher overall RMS than those of AT (*p*≤.010) (Table 2). Scans of all scanners led to higher marginal RMS than those of AT, regardless of the framework material (*p*≤.006 for PEEK and *p*<.001 for Ti) (Table 3).

4. DISCUSSION

When overall RMS values were considered, all scanners had different values than AT, except for PS and T3, when PEEK frameworks were digitized. Therefore, the first null hypothesis was rejected. The second null hypothesis was also rejected as AT had significantly lower marginal RMS values than other scanners.

It is critical to interpret carefully as statistically significant differences may not always be clinically relevant. When overall RMS values were considered, the estimated mean differences between test scanners and AT ranged between 2.39 µm to 13.41 µm for PEEK and 9.03 µm to 31.35 for Ti frameworks, while the maximum confidence interval value of estimated differences was 37.67 µm. The range is even tighter when considering the scans of only T3, PS and MT, which was between 2.39 and 21.38 µm. Differences in these values may be negligible when the methodology of the present study is implemented in an actual clinical situation, where the fabrication trueness of a complete-arch implant-supported framework is evaluated prior to actual appointment. As for the marginal RMS values, it is critical to emphasize that the measured deviations were of 4 abutment interfaces, and estimated mean differences in marginal RMS values between test scanners and AT ranged between 14.04 µm to 53.90 µm for PEEK and 16.94 µm to 40.50 for Ti frameworks. The range was, again, tighter for T3, PS, and MT, which was between 14.04 and 35.34 µm. Even though an equal distribution of measured deviations among different abutment sites of a complete-arch implant-supported framework is unlikely, the authors believe that scans of AT and tested scanners may be similar in situations with smaller frameworks on less number of implants. Therefore, it could be speculated that tested scanners may be feasible alternatives to AT while digitizing shorter span frameworks fabricated in non-reflective materials or reflective materials that are sprayed prior to scanning. However, this hypothesis needs to be supported with studies on the comparison of measured deviations of prosthetic structures with lesser units when digitized by using different scanners.

Another interesting finding when mean RMS values were evaluated was that, even though no statistical analysis was performed, IOSs mostly resulted in RMS values closer to AT than those obtained with LBSs. This could be associated with the fact that LBSs require an additional image processing step that stitches the separate scans of the occlusal and soft tissue surface of the framework, whereas digitization was performed in a single scan while using IOSs [6]. However, it should also be noted that MT had lower values compared with IOSs when PEEK frameworks were digitized and it had lower values than E4 for each material-scanned area pair. Considering that both MT and E4 utilize blue-light scanning technology and have similar features (4 integrated 5-megapixel cameras and 4 µm scan accuracy), the authors believe that this difference may be associated with their stitching algorithms. Among the studies that used MT [10, 27-31], the authors are aware of only 2 that compared MT and E4 [10, 31]. These scanners were reported to have similar accuracy with a maximum mean difference of 1.5 µm in trueness and 0.4 µm in precision while digitizing complete-arch implant-supported models [10] or complete-arch dentate models with varying number of prepared teeth [31]. However, Borbola et al. [31] have also reported that scans of

MT had higher precision than those of E4 when margins of the prepared teeth were considered, even though their trueness was similar. These findings may also highlight the possible effect of stitching on measured deviations as digitization of complete-arch models is commonly performed by using these LBSs, whereas digitization of an entire complete-arch implant-supported framework is rather unconventional for these LBSs and might have challenged E4 scanner, particularly at the margins.

Clinicians and dental technicians can benefit from the methodology of the present study to evaluate the fabrication trueness in clinical situations as instant evaluation of frameworks can facilitate the preparation for upcoming framework try-in appointments. However, digital trueness analyses should be accounted as an auxiliary assessment to intraoral misfit evaluation, which involves actual physical contact between the framework and the abutment [32]. Once the clinician finds calibration for measured deviations of a framework through scans and its clinical fit through radiographs and tactile evaluation, a pre-try-in appointment judgement may be made on the possibility of intraoral misfit of further frameworks to be fabricated. The findings of the present study and abovementioned small differences in mean values reflect such a potential for T3 and PS scanners for polymer, and MT scanner for Ti frameworks.

The primary purpose of the present study was to compare different IOSs and LBSs with an industrial-grade blue light optical scanner that is commonly used to generate reference scans in dental studies [24, 25, 33, 34]. The financial limitations determined the number of scans with AT, which was not readily available at the research site. Despite the fact that different frameworks were scanned by the scanners, it should be emphasized that all frameworks were made of the same STL file by using the pucks from one manufacturer and a commonly used, large size, and high-end 5-axis milling machine, to standardize the fabrication process, resulting in a total of 10 scans from 10 frameworks per material, scanning each once. In addition, tested scanners have been reported to have high precision in previous studies [31, 35]. Abovementioned factors to optimize and standardize the framework manufacturing protocol and small standard deviation values from the industrial scanner warrant the fabrication accuracy of frameworks and the soundness of the methodology.An anti-reflective scan spray was used to facilitate the scans of Ti frameworks, given their reflective surfaces [36]. Nevertheless, scans of all tested scanners led to higher RMS values than AT, which may be related to the possible inconsistent thicknesses of the powder on surfaces as the total amount of powder may vary even when the same operator applies the scan powder [36]. In addition, different scanning aid materials may lead to different results due to their inherent differences [36-38] such as the size of the injection nozzle [36]. It should also be mentioned that PEEK's inherent opaque structure may have contributed the results of the present study, and the scanners with significant differences compared with AT may have similar results if the PEEK frameworks were also powdered, which should be further investigated.

The RMS method, which is based on calculating the square root of the mean square of a set of numbers [39], was used to quantify the deviations in the present study. Even though the RMS method has been widely preferred in dental studies for deviation measurements [40], RMS values do not include directional information and different deviation measurement methods may affect the results [41]. In the present study, deviations were measured by using a 3D metrology-grade analysis software that was indicated in International Organization of Standardization standard 12836 [42]. Nevertheless, different software may lead to different results [43]. Another limitation of the present study was that the effect of material on measured deviations was not investigated. Considering that this study was the first to compare an industrial-grade scanner with IOSs and LBSs while digitizing a prosthetic framework, the preliminary results of the present study need further support to broaden the knowledge on the applicability of tested scanners as a reference scanner for studies on deviations of prosthetic structure and for deviation measurements in dental clinics and laboratories.

5. CONCLUSIONS

Based on the results of this in-vitro study, the following conclusions can be drawn:

1. PS and T3 can be considered to scan PEEK frameworks for overall surface analyses as their scans were similar to those of AT. However, for Ti frameworks, AT should be used as all tested scanner scans were different than that of AT.

2. However, scans of all tested scanners may reveal excessively high deviations at margins, regardless of the material of the complete-arch implant-supported framework.

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Scanner	Manufacturer	Abbreviation
ATOS Core 80	GOM GmbH, Braunschweig, Germany	AT
E4 Dental Scanner	3Shape, Copenhagen, Denmark	E4
T710	Medit, Seoul, Republic of Korea	MT
Primescan	Dentsply Sirona, Bensheim, Germany	PS
TRIOS 3	3Shape, Copenhagen, Denmark	T3
TRIOS 4	3Shape, Copenhagen, Denmark	T4

TABLES

Table 1. Scanners used in this study

Table 2. Mean values and standard deviations (SD), estimated mean differences, and 95% confidence interval (95% CI) values for overall RMS measurements (µm) for each scanner within each material

	PEEK		Titanium	
	Mean ±SD (95% CI)	Estimated Mean Difference (95% CI)	Mean ±SD (95% CI)	Estimated Mean Difference (95% CI)
AT	117.32 ±4.03^{A} (114.82–119.82)		63.43 ±14.67^{A} (54.34–72.52)	
E4	130.73 ±4.15^{B} (128.17–133.30)	13.41 (10.07–16.75)	94.78 ±18.10^{B} (83.56–106)	31.35 (25.03–37.67)
MT	111.68 ±2.43^{B} (110.17–113.19)	-5.64 (-8.98–-2.30)	72.46 ±11.75^{B} (65.18–79.74)	9.03 (2.71–15.35)
PS	114.93 ±1.83^{A} (113.80–116.06)	-2.39 (-5.73–0.95)	84.81 ±3.01^{B} (82.94–86.68)	21.38 (15.06–27.70)
T3	114.13 ±2.71^{A} (112.45–115.81)	-3.19 (-6.53–0.15)	84.11 ±10.67^{B} (77.50–90.72)	20.68 (14.65–26.71)
T4	123.95 ±7.39^{B} (119.37–128.53)	6.63 (3.29–9.97)	89.95 ±11.32^{B} (82.93–96.97)	26.52 (20.20–32.84)

*Different superscript uppercase letters indicate the significant difference of a scanner when compared with the reference scanner (AT) in each column ($P<.05$)

Table 3. Mean values and standard deviations (SD), estimated mean differences, and 95% confidence interval (95% CI) values for marginal RMS measurements (µm) for each scanner within each material

	PEEK		Titanium	
	Mean ±SD (95% CI)	Estimated Mean Difference (95% CI)	Mean ±SD (95% CI)	Estimated Mean Difference (95% CI)
AT	20.99 ±4.37[A] (18.28–23.70)		30.13 ±5.24[A] (26.88–33.38)	
E4	74.89 ±7.05[B] (70.52–79.26)	53.90 (44.64–63.16)	70.63±10.85[B] (63.90–77.36)	40.50 (34.84–46.16)
MT	56.33 ±17.10[B] (45.73–66.93)	35.34 (26.08–44.60)	59.53 ±12.29[B] (51.91–67.15)	29.40 (23.74–35.06)
PS	45.45 ±9.87[B] (39.33–51.57)	24.46 (15.20–33.72)	47.07 ±2.35[B] (45.62–48.52)	16.94 (11.28–22.60)
T3	35.03 ±4.12[B] (32.48–37.58)	14.04 (4.78–23.30)	51.86 ±7.03[B] (47.50–56.22)	21.73 (16.07–27.39)
T4	52.37 ±16.07[B] (42.41–62.33)	31.38 (22.12–40.64)	52.66 ±5.66[B] (49.15–56.17)	22.53 (16.87–28.19)

*Different superscript uppercase letters indicate significant difference of a scanner when compared with reference scanner (AT) in each column (P<.05)

FIGURES

Figure 1. Overview of study design

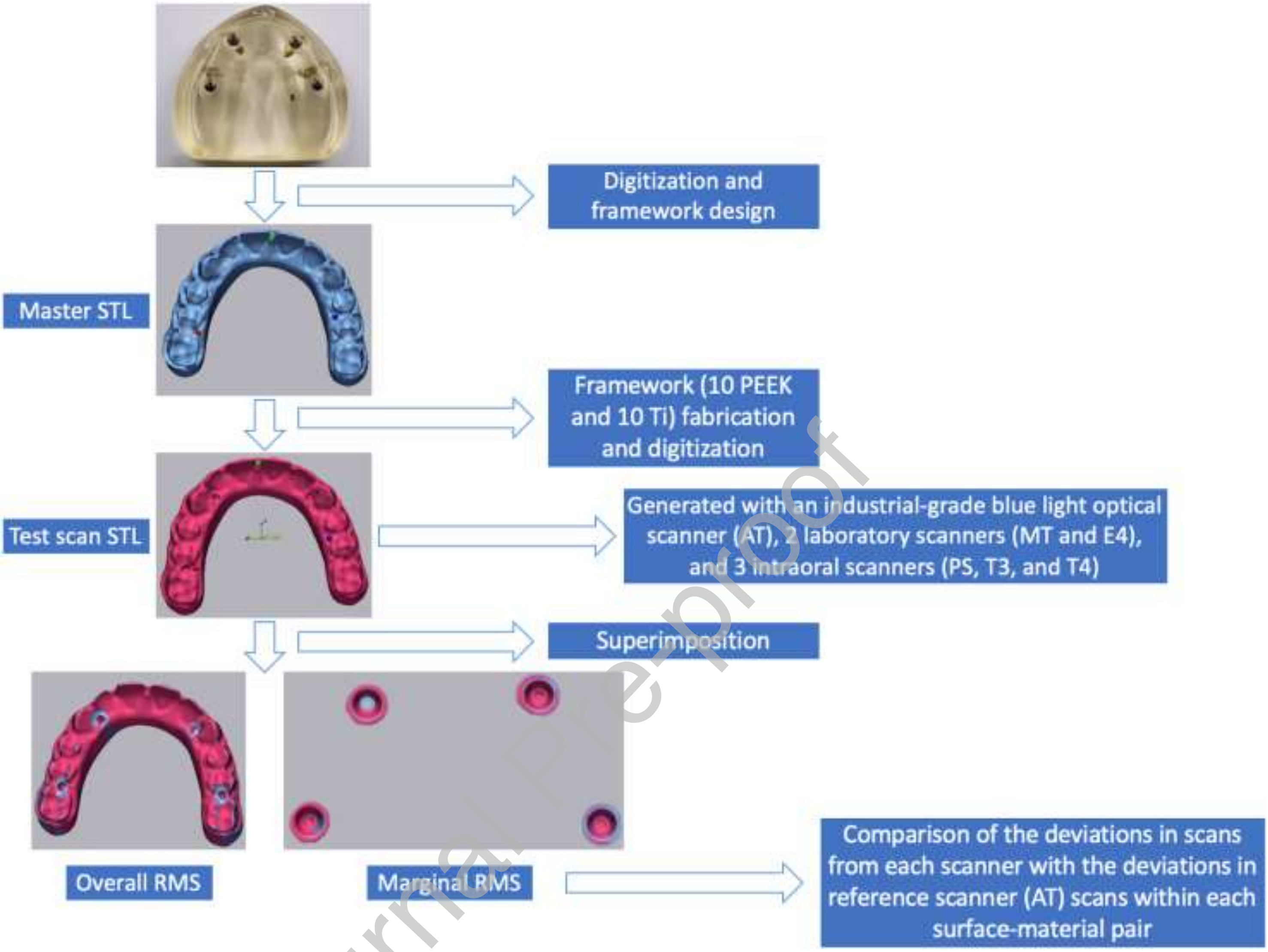


Figure 2. Master model used to generate M-STL file

Figure 3. Points selected for initial superimposition of STL files (A: Overall RMS; B: Marginal RMS)

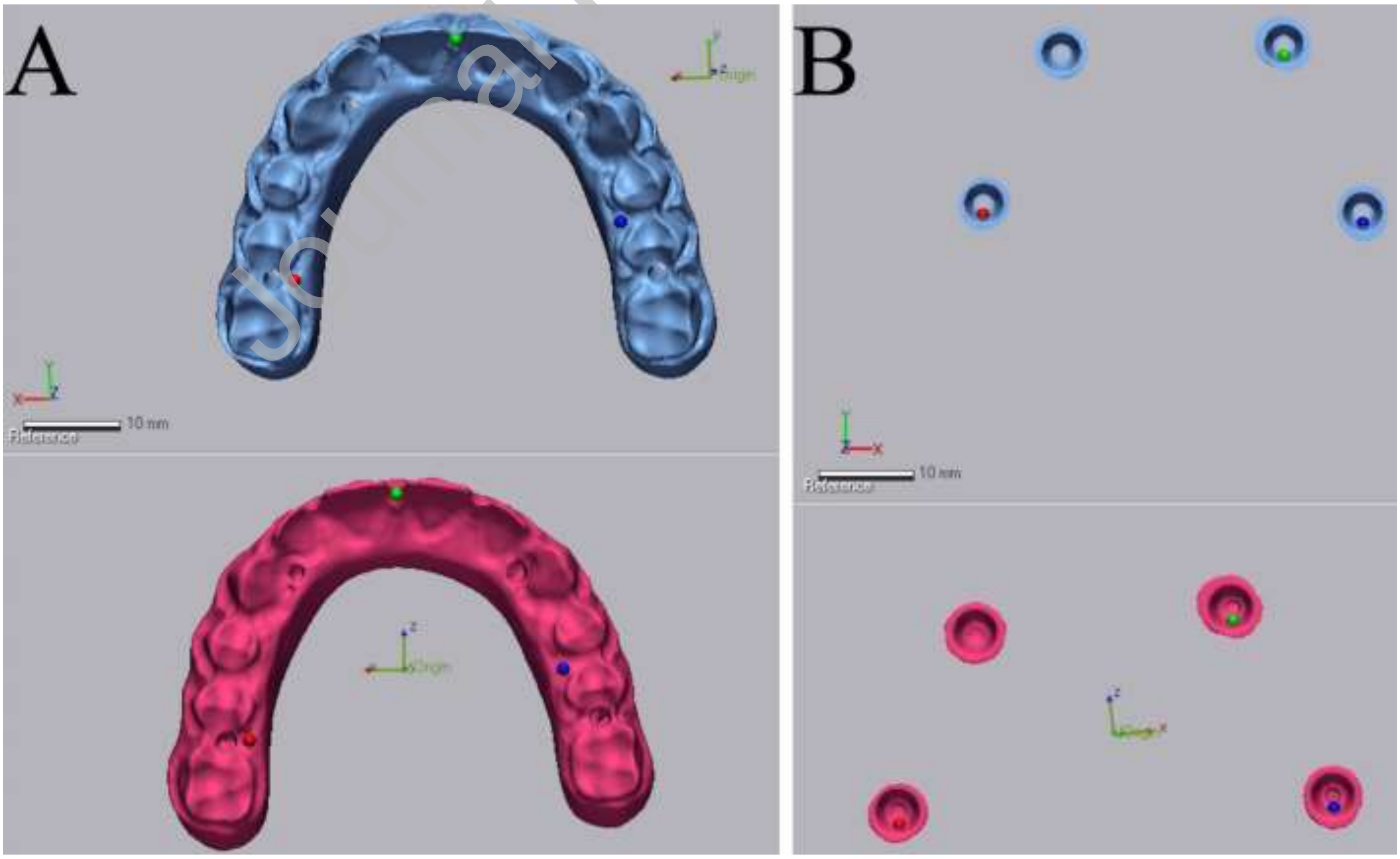


Figure 4. Color maps generated for overall and marginal RMS measurements of PEEK framework (A: Occlusal surface; B: Frontal view; C: Soft tissue surface; D: Isolated margins)

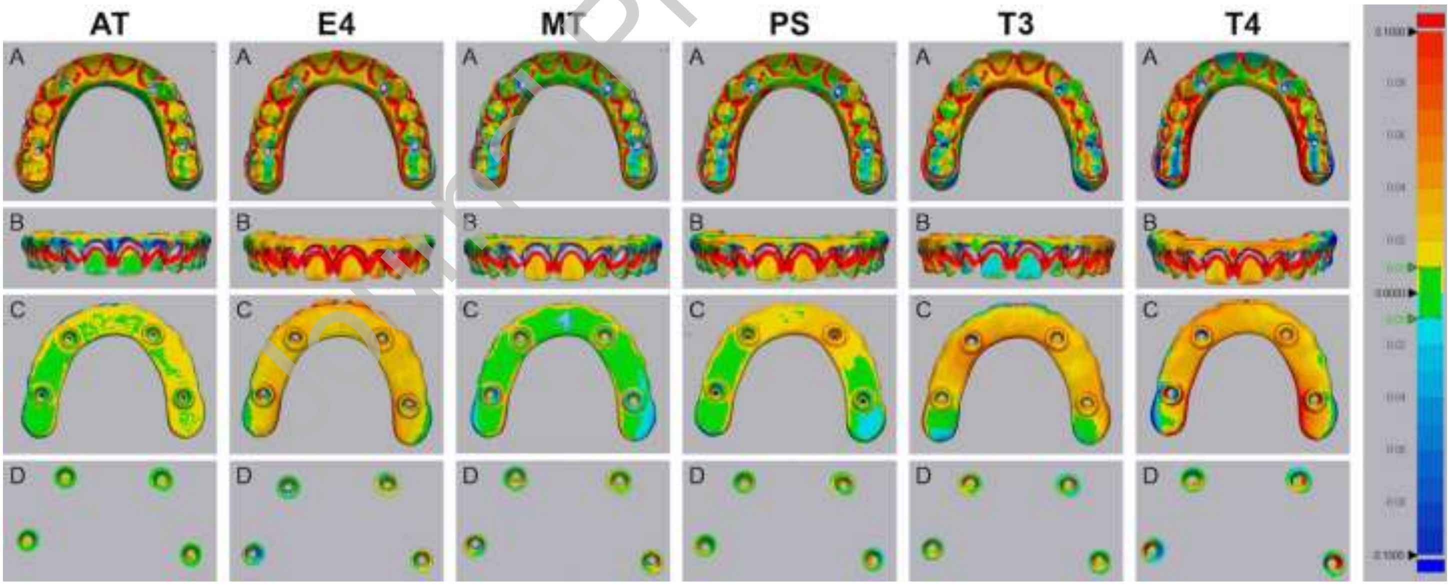


Figure 5. Color maps generated for overall and marginal RMS measurements of Ti framework (A: Occlusal surface; B: Frontal view; C: Soft tissue surface; D: Isolated margins)

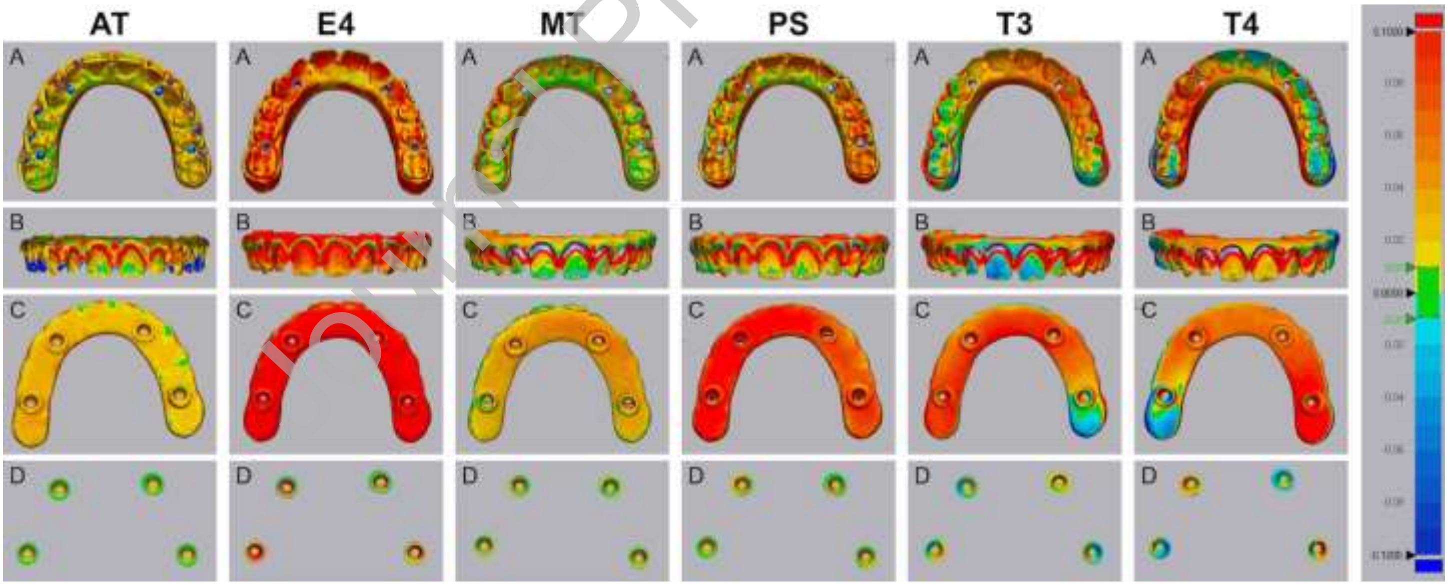


Figure 6. Box-plot graph of overall RMS values for each scanner-material pair (A: PEEK; B: Ti)

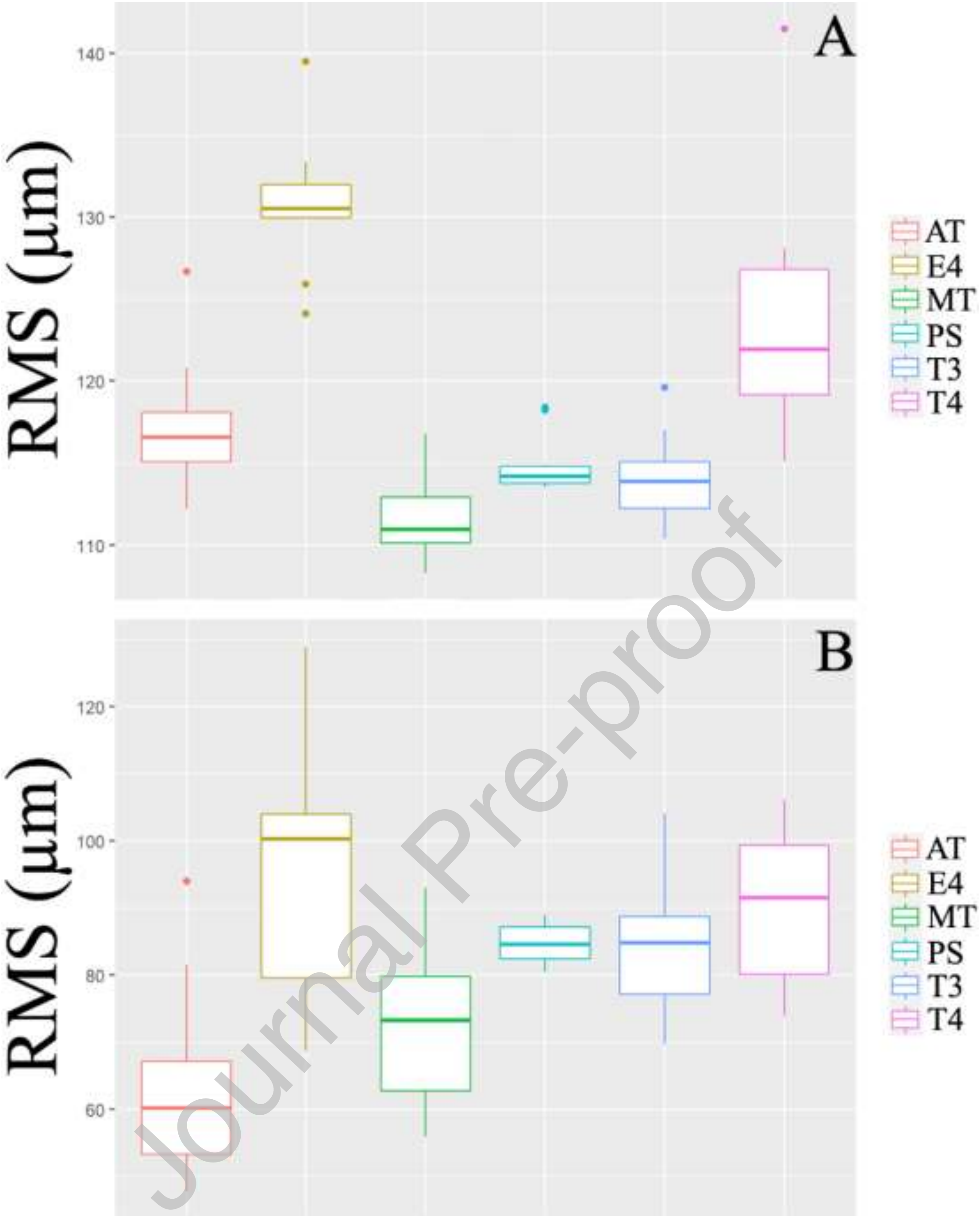
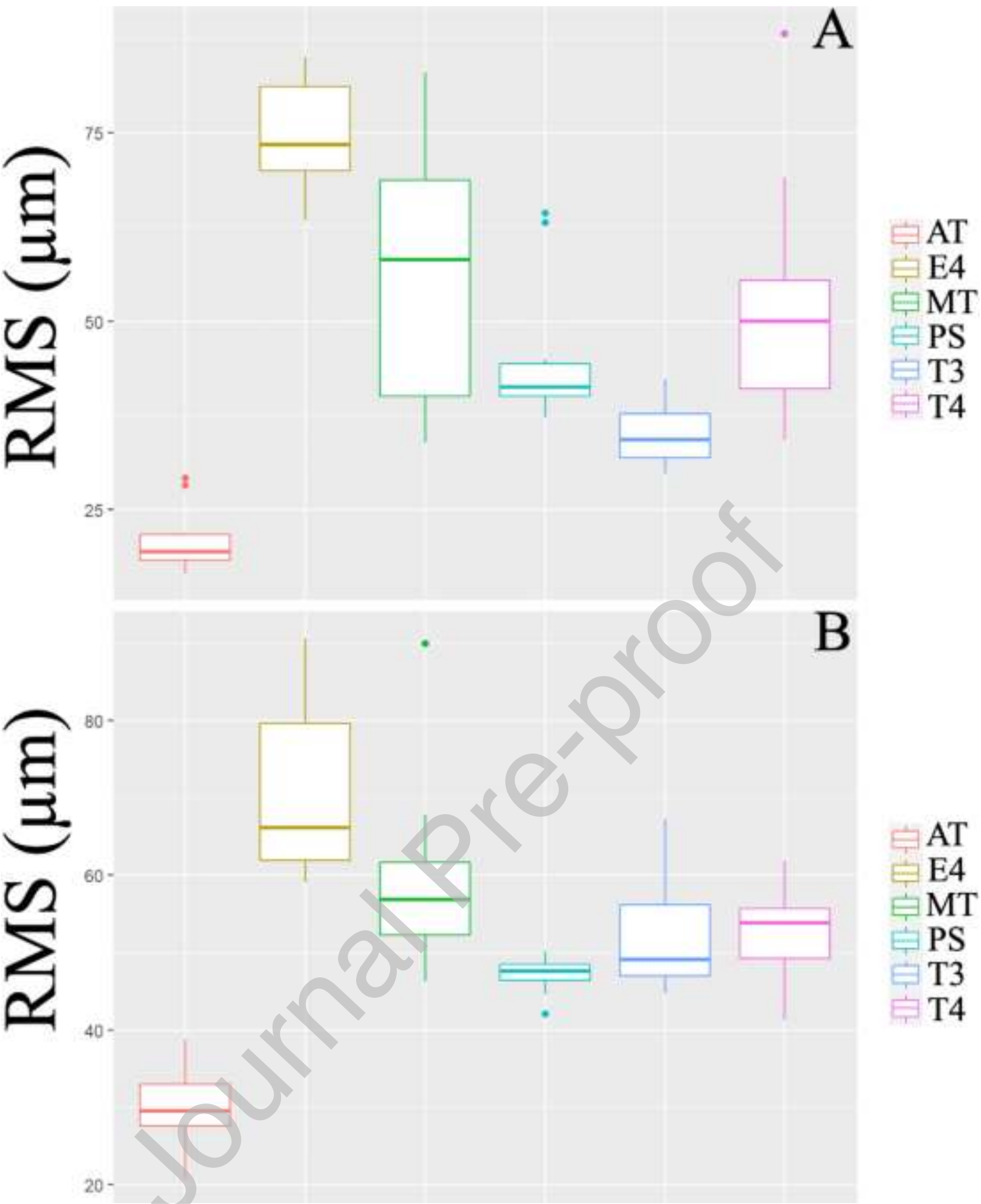


Figure 7. Box-plot graph of marginal RMS values for each scanner-material pair (A: PEEK; B: Ti)



Author Statement

The authors of the manuscript contributed in the following ways to the submitted manuscript:

Burak Yilmaz: Critical revision of the article, Approval of the submitted and final versions

Doğu Ömür Dede: Design, Data collection

Mustafa Borga Donmez: Drafting article, Critical revision of article

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: