

## Article

# Assessment of Dental Arch Reproduction Quality by Using Traditional and Digital Methods

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**Abstract:** Background: There exists few scientific reports on the quality of digitally reproduced dental arches, even though digital devices have been used in dentistry for many years. This study assesses the accuracy of the standard dental arch model reproduction using both traditional and digital methods. Methods: The quality of the full upper dental arch standard model reproduction by physical models obtained through traditional and digital methods was compared: gypsum models (SGM) and models printed from data obtained using an intraoral scanner (TPM) ( $n = 20$ ). All models were scanned with a reference scanner. Comparisons were made using *Geomagic Control X* program by measuring deviations of the models relative to the standard model and analyzing linear dimensions deviations. Results: The average error of reproduction accuracy of the standard model ranged from  $0.0424 \pm 0.0102$  millimeters (mm) (SGM) to  $0.1059 \pm 0.0041$  mm (TPM). In digital methods, all analyzed linear dimensions were shortened to a statistically significantly degree compared to traditional. The SGM method provided the smallest deviations to a significant degree of linear dimensions from the pattern, and TPM the largest. The intercanine dimension was reproduced with the lowest accuracy, and the intermolar the highest in each method. Conclusions: Traditional methods provided the highest reproduction trueness of the full dental arch and all analyzed linear dimensions. The intercanine dimension was reproduced with the lowest accuracy, and the intermolar the highest in each method, where digital methods shortened all analyzed linear dimensions.

**Keywords:** 3D printed model; addition silicone impression material; digital impression; gypsum model; intraoral scanner; linear measurements



**Citation:** Wójcik, M.; Skaba, D.; Skucha-Nowak, M.; Tanasiewicz, M.; Wiench, R. Assessment of Dental Arch Reproduction Quality by Using Traditional and Digital Methods. *Appl. Sci.* **2021**, *11*, 1263. <https://doi.org/10.3390/app11031263>

Received: 14 January 2021

Accepted: 27 January 2021

Published: 30 January 2021

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## 1. Introduction

Digital dentistry is developing very quickly, offering more and more opportunities. Intraoral scanners are subject to constant improvement, providing comfort and work efficiency. Moreover, the range of indications in which they can be used is constantly growing.

The increasing integration of computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies and the progress in the field of biomaterials make it possible to reduce the number of visits, shorten their duration and reduce the costs of restorations [1–3]. It is possible to skip many factors related to taking a conventional impression or casting a model, which may have a negative impact on the quality of the final restoration [4]. Many authors emphasize that digital methods reduce the time of taking an impression and are preferred by patients, but many other authors believe that this is a less important parameter and the focus should be on the accuracy of the obtained images [5].

Intraoral scanners differ in shape, price, weight, size and the way the tip is guided during scanning, i.e., the scanning path. They also provide differentiated working speed and indications. Currently, the standard are powder-free scanners, capturing an image in a color similar to natural, often available in a mobile version, which significantly facilitates work in several dental offices. Existing devices are based on several non-contact optical technologies such as confocal microscopy, photogrammetry or optical triangulation [6]. The scanner should be able to detect all the details of the scanned physical object, to generate a virtual three-dimensional model that is as close to it as possible. It is a common belief that scanning accuracy increases with increasing device resolution. However, there are scientific investigations in which the accuracy of the obtained digital models was usually lower for scanners characterized by higher resolution [7,8]. Kihara et al. in their review of the literature on the accuracy achieved by intraoral scanners, they report that it is influenced by many factors. These include, for example, the scanner model, software version, the extent of the scanned dental arch, the presence or missing teeth, an implant or even color temperature, illuminance [9]. If intraoral scanners will provide similar or higher accuracy and will significantly reduce working time, they can be an alternative to traditional methods.

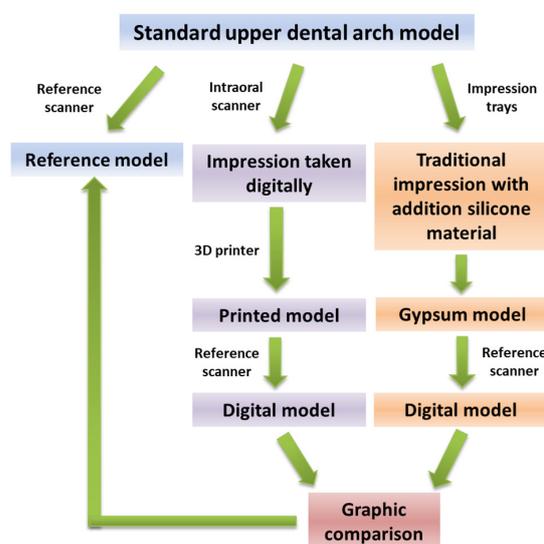
Some research also show that the disinfection protocols in dental offices are not sufficiently followed, which results in the transfer of microorganisms (bacteria, viruses, including SARS-CoV2) to the dental laboratory. The patient's biological fluids containing microorganisms are transferred to the impressions, which, if not properly decontaminated, can be transferred to the plaster models [10].

In the digital procedure, after scans are performed by the office staff, virtual models of the patient's dental arches received in the form of digital files are sent via internet to the laboratory without any contact between individuals. The tip of the scanner, which is in contact with the tissues of the patient's oral cavity during scanning, is removed and sterilized in an autoclave, which prevents the transmission of microorganisms between patients.

Scientific reports comparing the accuracy of dental arches reproductions produced with digital methods versus traditional methods are rare and difficult to access. This fact prompted us to undertake research in this direction. The aim of this study was to assess the quality of the full upper dental arch standard model reproduction using traditional and digital methods.

## 2. Materials and Methods

Standard model of the full upper dental arch (Real Series Model DT.1200.01 from Falcon, Poland, in a size and color close to natural) was used in the study (Figure 1).



**Figure 1.** The scheme of mutual comparison of models obtained by traditional and digital methods to the reference model.

### 2.1. Digital Impressions Using Intraoral Scanner

First, ten impressions of dental arch standard model (phantom) were obtained by digital method using the 3Shape Trios 3 intraoral scanner in the portable version Pod powered by software version 1.3.4.5. The cleanliness of the optical elements was checked and the scanner calibrated according to the manufacturer's recommendations before scanning began. Models based on digital impressions were printed by a 3D printer (Prodways ProMaker L7000 D) used in dentistry as a standard. The manufacturer claims 3D-printing accuracy at the level of 0.04 mm.

### 2.2. Traditional Impressions Using Addition Silicone Material

Then ten impressions of the phantom were taken with an additive silicone material (Heraeus Kulzer Variotime Dynamix Monophase) on standard perforated metal impression trays with a rim (Pol-Intech Poland). The impression tray filled with material was left on the factory model to set for twice as long as recommended for use in the patient's mouth; a stopwatch measured setting times. All impressions of the standard model were taken by one dentist (M.W.) on the same day under the same dental-office lighting and at room temperature. Traditional impressions were placed in airtight containers that prevented changes in humidity. They were stored at room temperature in the dark, dry environment of the prosthetic workshop until models were cast.

To prepare dental arch models from traditional impressions, dental hardness class IV gypsum (GC Fujirock EP IV) was used. Gypsum models were cast in accordance with the manufacturers' recommendations within 3 to 24 h.

All prepared models were stored similarly to traditional impressions until they were scanned with a reference scanner.

### 2.3. Scanning of the Models with a Reference Scanner

The reference (extraoral) scanner 3Shape E3 [11,12], in combination with the dedicated ScanIt Dental 2017 1.17.3.1 software, was used to create digital equivalents of the factory model as well as gypsum (SGM) and printed (TPM) models obtained in the course of this research. This scanner was chosen for its very high degree of accuracy, declared by the manufacturer to be  $\pm 0.01$  mm. The received digital models were trimmed along the cervix of the teeth using the graphic program, Dental Designer, a component of the Dental Desktop package (3Shape, Poland). This operation was carried out in order to minimize the gum surface present in the results.

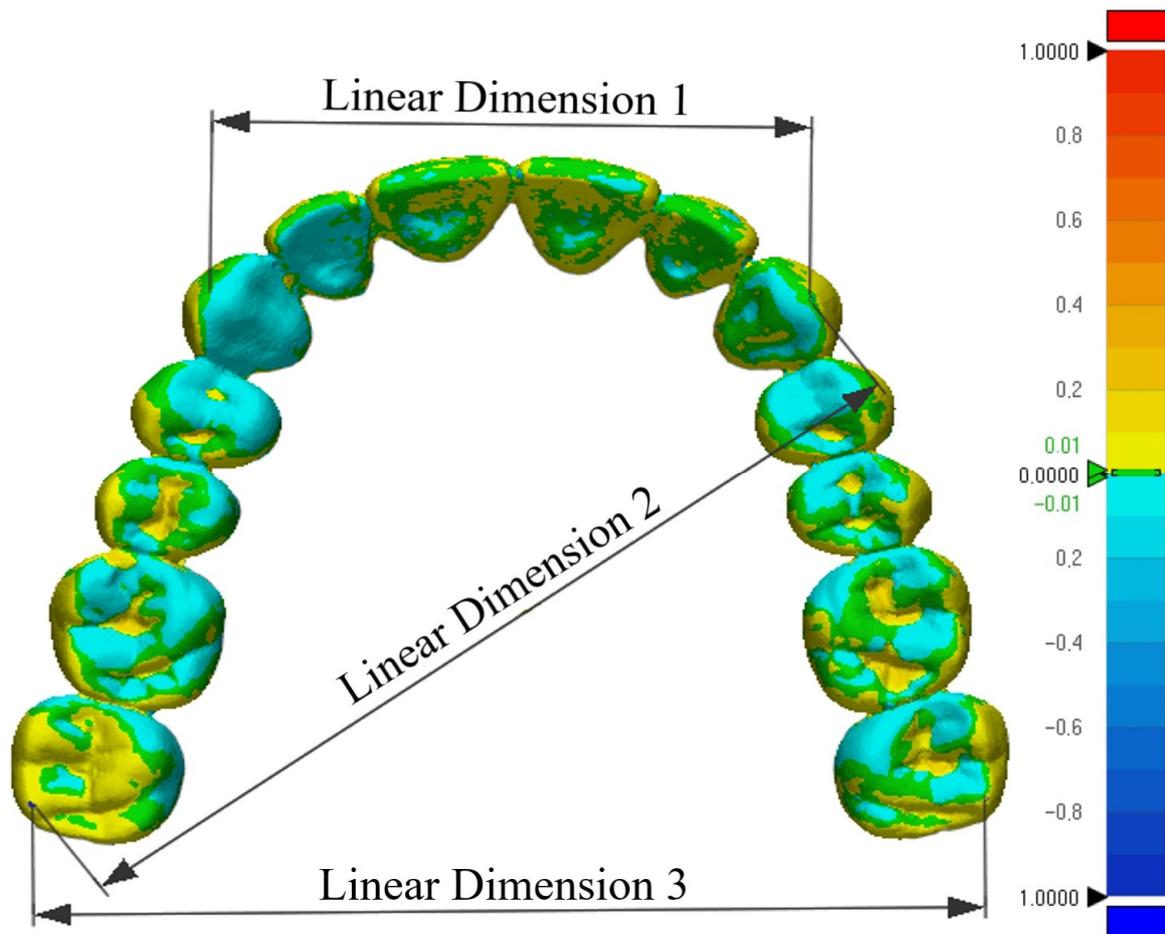
### 2.4. Models Comparisons

Virtual dental arch models were superimposed in a specialized graphic control program Geomagic Control X version 2018.0.1 in order to compare each of the ten models of both groups to the reference model according to the diagram shown in Figure 1.

#### 2.4.1. Measurement of Conformity of Models Obtained by Traditional and Digital Methods

In the research, the "best-fit" function, was used for superimposition comparative digital models relative to the largest number of compatible points in both models. Deviations are displayed in the form of a color map, corresponding to specific ranges of values of these deviations from the reference model (Figure 2).

The color bar next to the compared models shows range of deviations of the test model from the reference model and indicates whether the analyzed test model is within the 0.01 mm tolerance limit marked in green. Values above 0.01 mm, marked in yellow to red, indicate the measured data is larger (higher) than the surface or edge of the reference data. The darker the color, the greater the difference in the area. Light blue to dark blue indicate that the measured data are smaller (lower) than the reference data.



**Figure 2.** Map of deviations along with determined linear dimensions.

#### 2.4.2. Measurement of Marked on Models Linear Dimensions

The tool called Simulated CMM Point imitates a real coordinate-measuring machine in the way it works in the real world. The virtual object is treated as real, which makes it possible to obtain measuring points with the help of a virtual probe as it would be in real-world conditions. After setting at least two simulated points on the reference model, it becomes possible to directly measure the distance between them, the distance then becomes a reference value. The linear dimension obtained in this way is expressed in millimeters. The points present on the test model, paired with the points selected with the help of the measuring probe, are found automatically by the program after using the best-fit method. On this basis, the program determines the difference (deviation) between the value of the linear dimension between two points on the test model to the corresponding points on the reference model. When measuring the distance between selected points, the calculations simulate the caliper used in reality for manual measurement.

The points were established near the tops of the incisal cusps of the canines and distal cheek cusps of the second molars. The tested linear dimensions were marked with numbers from 1 to 3. Linear dimension 1 (LD1) concerned the distance between the points established near the tops of the incisal cusps of the canines. Linear dimension 2 (LD2) extended from the top of the incisal cusp of the canine to the distal buccal cusp of the second molar on the opposite side of the dental arch. Linear dimension 3 (LD3) span the distance between distal buccal cusps of the second molars on opposite sides of the arch.

### 2.5. Statistical Analysis

Tests used for analysis included the t-test for two independent samples, ANOVA test, and Kruskal-Wallis test, Mann-Whitney U test, as well as the Shapiro-Wilk normality distribution test.

A significance level of 0.05 was used for statistical analysis. When  $p$ -values less than 0.05 were obtained, statistical differences were deemed significant. The STATISTICA 13.3 program was used to perform the calculations.

The following variables were considered in the statistical analysis:

- Root Mean Square (RMS):  $\text{RMS} = \frac{1}{\sqrt{n}} \cdot \sqrt{\sum_{i=1}^n (x_{1,i} - x_{2,i})^2}$ , where  $x_{1,i}$  is measuring point  $i$  on the reference model,  $x_{2,i}$  is measuring point  $i$  on the test model, and  $n$  is the total number of measurement points per model.
- Standard deviation (SD) is the standard deviation of the deviations.

The trueness of the pattern model reproduction was assessed by determining the average of RMS values among all models from each group separately.

The results of deviations of individual linear dimensions: LD1, LD2, LD3 were analyzed. Therefore, the “Dev. LD1”, “Dev. LD2”, “Dev. LD3” were analyzed to identify differences between segment lengths on models under study and segment length on the reference model for each linear dimension.

In addition,  $V_{LD1}$ ,  $V_{LD2}$ , and  $V_{LD3}$  were analyzed. The  $V_{LDi}$  coefficient determines what percentage of reference values are deviations of the tested linear dimensions, where

$$V_{LDi} = (\text{LDi dev.}/\text{LDi ref. value}) \cdot 100\%, i = 1, 2, 3,$$

LDi ref. value = segment length in the reference model for the  $i$ th linear dimension;

LDi dev. = difference between the segment length obtained in the tested method and the segment length determined on the reference model for the  $i$ th linear dimension.

Positive values indicate an increase and negative values indicate a shorter length of a given section compared to the reference model.

## 3. Results

### 3.1. Comparison of Traditional and Digital Models

After superimposition of the models using the best-fit method, the highest trueness of pattern model reproduction was provided by the SGM method for which the average RMS value was  $0.0424 \pm 0.0102$  mm. In the case of the TPM method, a statistically significant higher average RMS value of  $0.1059 \pm 0.0041$  mm was noted (Table 1).

**Table 1.** Trueness of SGM and TPM method.

Method	RMS		
	Mean (mm)	SD (mm)	$p$ -Value
SGM	0.0424	0.0102	0.0205
TPM	0.1059	0.0041	0.1536

### 3.2. Analysis of Linear Dimensions

The following results concern analysis of linear dimension deviations from the reference values of the reference model (Figures 3–5).

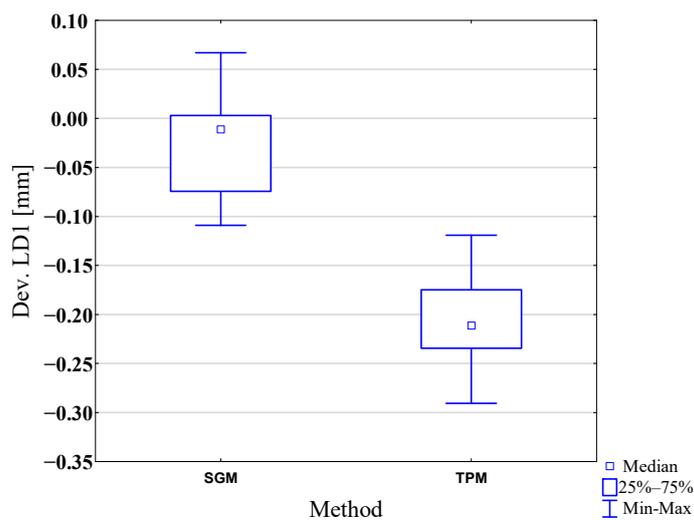


Figure 3. Comparison of deviations of the linear dimension 1 for SGM and TPM methods.

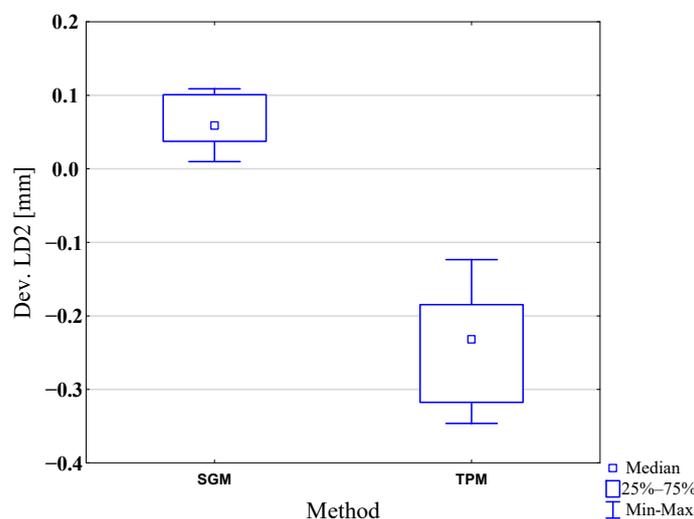


Figure 4. Comparison of deviations of the linear dimension 2 for SGM and TPM methods.

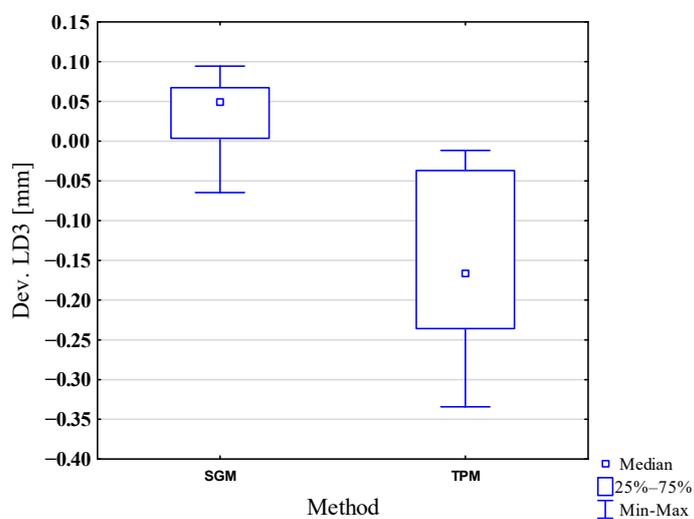
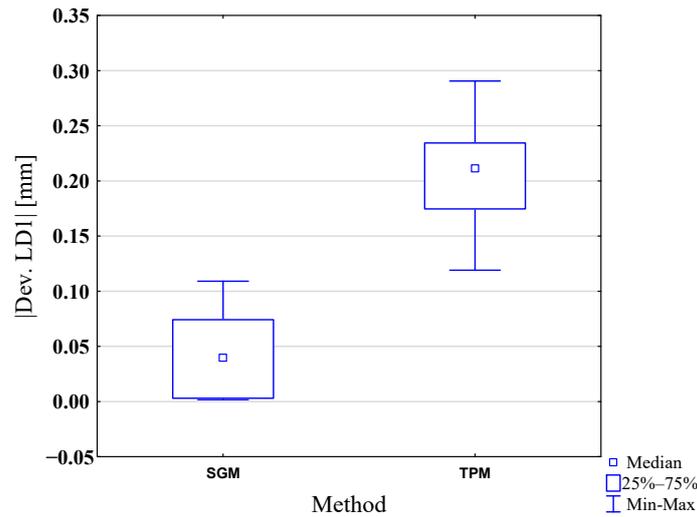


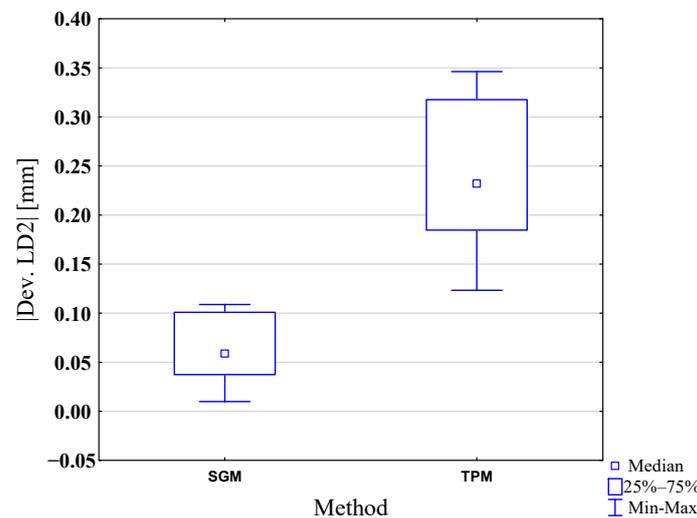
Figure 5. Comparison of deviations of the linear dimension 3 for SGM and TPM methods.

In digital methods, each linear dimension was significantly shortened relative to traditional methods. Furthermore, all measurements in digital methods are negative because all maximum values are negative (LD1:  $-0.1191$  mm; LD2:  $-0.1234$  mm; LD3:  $-0.0116$  mm), indicating each of the analyzed dimensions was shortened in the TPM method in every model.

Figures 6–8 present the results of statistical analysis regarding the absolute values of the considered deviations, in order to compare deviation size of each of the analyzed linear dimensions from the pattern within individual study groups.

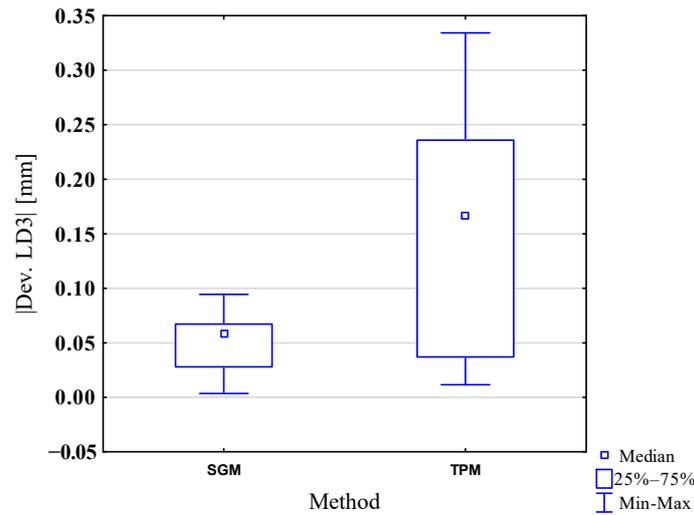


**Figure 6.** Comparison of the absolute values of the linear dimension 1 deviations for SGM and TPM methods.



**Figure 7.** Comparison of the absolute values of the linear dimension 2 deviations for SGM and TPM methods.

For all three analyzed linear dimensions, the smallest arithmetic means of absolute deviations from the standard occur for the SGM method (LD1:  $0.0444$  mm; LD2:  $0.0640$  mm; LD3:  $0.0527$  mm) and statistically the largest for TPM (LD1:  $0.2040$  mm; LD2:  $0.2362$  mm; LD3:  $0.1523$  mm).



**Figure 8.** Comparison of the absolute values of the linear dimension 3 deviations for SGM and TPM methods.

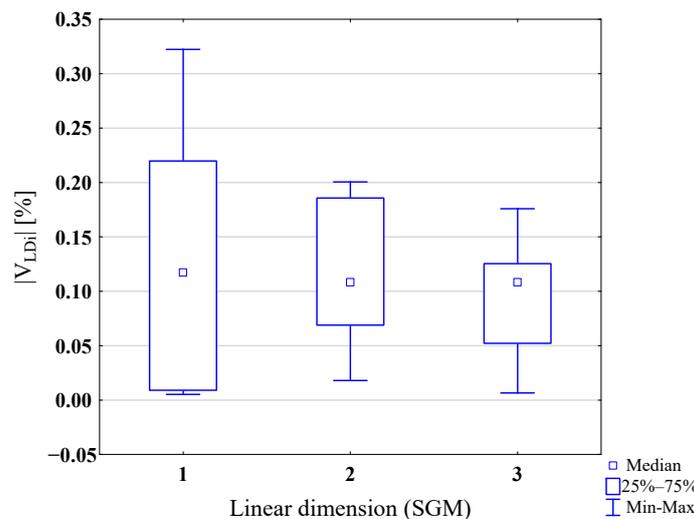
The above data concerned finding relationships between a given linear dimension and the method used to make dental arch models.

In order to compare the quality of the three linear dimensions' reproduction within a given method, the absolute values of the  $V_{LDi}$  coefficient were used, where

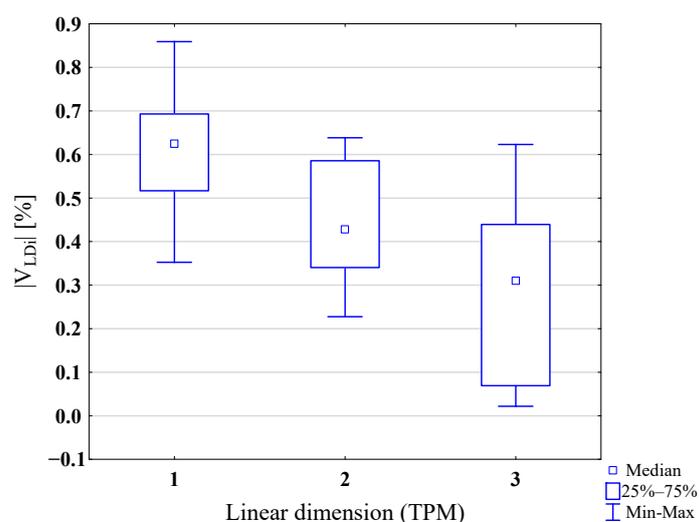
$$\begin{aligned} \text{reference value LD1} &= 33.8158 \text{ mm} \\ \text{reference value LD2} &= 54.2461 \text{ mm} \\ \text{reference value LD3} &= 53.6670 \text{ mm} \end{aligned}$$

Of all the analyzed sections, LD3 was reproduced with the highest accuracy by each of the methods (SGM: 0.0982%; TPM: 0.2839%) while LD1 was least accurately reflected (SGM: 0.13112%; TPM: 0.6032%). The SGM method reproduced all sections most accurately, without statistically significant differences between individual linear dimensions.

LD1 was reproduced statistically least accurately in the TPM method, compared to other linear dimensions (Figures 9 and 10).



**Figure 9.** Distribution of absolute values of the  $V_{LDi}$  coefficient for the examined linear dimensions (SGM).



**Figure 10.** Distribution of absolute values of the  $V_{LD_i}$  coefficient for the examined linear dimensions (TPM).

#### 4. Discussion

Various procedures for measuring digital dental arch models were used, to assess the accuracy of the digital impression method. Superimposing digital models using a 3D analysis program is the most commonly used method to measure and visualize surface deviations between digital models and the reference model [8,13–15]. Measuring linear distances between specific points located on the teeth or between reference objects attached to the model is also common practice [16–18].

Another method of assessing accuracy is scanning calibrated objects which dimensions are known [19] or measuring the marginal fit of final permanent prosthetic restorations [20–22]. However, these calibrated objects are small and do not have typical morphology of teeth or dental arches. In turn, the restoration fit assessment includes the entire production process, not just the assessment of the preparation scan quality [23].

Some sources of inaccuracy include 3D data registration by digital scanners and data processing by the CAD/CAM software program. The process of milling or printing dental models produces its own inaccuracies but also includes errors that occur at all stages [24].

We made the decision to assess the reproduction of the entire dental arch after printing the models, for this study. In the available literature, most researchers evaluated intraoral scanners by using 3D comparative analysis, measuring only virtual models without producing real master models [8,13–15]. Only a few studies compared dimensional error after creating the physical model [25–27]. Some previous studies were based on only a single tooth, without checking representation of the entire arch [28]. Their clinical value is therefore limited because the authenticity of the reproduction assessed in them cannot be related to more extensive and complicated clinical situations. For single tooth, Hack et al. [29] obtained high values of the trueness of virtual models, due to the examined intraoral scanners with an RMS variable value range from  $0.0069 \pm 0.0009$  mm for the TRIOS 2 scanner to  $0.0452 \pm 0.0171$  mm in the case of the Omnicam camera.

In turn, for the entire arch, Patzelt et al. [30] achieved the trueness of tested intraoral scanners at the level of 0.038 to 0.3329 mm for the model with 14 prepared teeth, while Ender et al. [31] found trueness to vary from 0.0294 to 0.0449 mm.

In the present study, traditional methods using impressions with addition silicone material (SGM) ensured the highest trueness (RMS =  $0.0424 \pm 0.0102$  mm) in the reproduction of the phantom. Digital methods (TPM) provided lower trueness (RMS =  $0.1059 \pm 0.0041$  mm) to a statistically significant degree.

In in vitro studies conducted by Jin et al. [26], comparison of models in the Geomagic program did not show statistically significant differences between printed models (SLA), which achieved accuracy at the level of  $0.1143 \pm 0.0018$  mm, and gypsum, with value of

0.11112 ± 0.0031 mm. The authors stated that the accuracy value achieved by models printed from photopolymer materials (SLA) is sufficient for clinical applications.

Since previous digital model accuracy tests recommended a measurement error of less than 0.2 mm as acceptable in clinical settings [26,32], the average accuracy of the models printed in this study was 0.1059 mm, indicating their potential for use in clinical settings.

Studies focused on full-arch scans using intraoral scanners have found large deviations in the lateral segment of the dental arch on the opposite side to the point where the scan was started [33]. The limited complexity of the front teeth geometry contributes to the accumulation of errors in matching the sequentially captured images [23,31,34]. Small errors in this region, especially those affecting angular relationships, add relatively large deviations at the end of the arch [17,18].

A review of relevant literature published in 2017, delivered the conclusion that the accuracy of intraoral scanners used for clinical application is satisfactory and similar to the accuracy level of conventional methods. This conclusion is based on the study of natural teeth, implants, and permanent dentures up to 4–5 points [35].

Wesemann et al. [17] assumed that, in the case of whole-arch scans, deviations smaller than 0.14 mm can be classified as very good and below 0.25 mm as acceptable. They assessed the clinical results for Trios 3 as very good. The entire process from taking the intraoral scan to printing the model was characterized by acceptable accuracy in their examination.

According to these criteria, it can be concluded that the whole process from taking the intraoral scan to printing the model was characterized by very good accuracy in the current study.

Most in vitro surveys [20–22,29] showed that intraoral scanners achieve accuracy close to or higher than conventional methods in single-point scans, in contrast to whole-arch scans, where they do not match traditional methods [23,31].

The divergent results reported in the studies can be explained by differences in the methodology used, including differences in the reference model, scanning strategy, scanning software, and analysis program [8,36].

No statistically significant differences were found between measurements made directly on physical models using a digital calliper and those on digital models in the research of Sousa et al. [37]. On this basis, researchers concluded that linear measurements on virtual models created after scanning physical models with an extraoral scanner are highly accurate and one can rely on the results obtained from measuring the width and length of the arch both in clinical practice and during scientific research. Researchers were the first to use the Geomagic program instead of the software included with the scanner to determine points and measure the distance between them, studying its accuracy at the same time.

In this study, the latest version of the Geomagic Control X quality control program was used for measurement. The program automatically searches for matching points on the test model after selecting them on the reference model based on a previous 3D comparison. This eliminates human error in the selection of corresponding points on the compared models.

Conventional methods (SGM) compared to digital (TPM) resulted in the smallest deviation, by a statistically significant degree, from the standard for all linear dimensions. In addition, digital methods significantly diminished each time all sections compared to traditional (LD1: −0.2040 mm; LD2: −0.2362 mm; LD3: −0.1523 mm).

The linear dimension between the second molars (LD3) was reproduced with the highest accuracy by each method (SGM: 0.0982%; TPM: 0.2839%). Elastomer impression materials shrinkage of approximately 0.15% to 0.5%, is at least partly compensated by expansion of dental plaster during setting which is approximately 0.07% to 0.1% [38,39].

Although the distance between the canines (LD1) was the shortest, it was reproduced the least accurately by each of the methods (SGM: 0.13112%; TPM: 0.6032%). Other authors reported that the shorter the distance between the points measured on the model, the greater the accuracy of linear dimension reproduction achieved by both traditional and

digital methods [18]. As it is visible, this determination does not apply to the anterior segment of the dental arch in the current study.

The SGM method reproduced all sections most accurately, without statistically significant differences between individual linear dimensions, while the TPM method reproduced LD1 with accuracy diminished to a statistically significant degree in comparison to the other sections.

Wesemann et al. [17], concluded on the basis of linear measurements in their in vitro study that, intraoral scanners are an alternative for scanning full arches in orthodontics, while for prosthetics, the scanning distance should be one quarter [40].

There is little research on the accuracy of dental models created by 3D printing. Most of them show sufficient accuracy and may be suitable for clinical use [25,26,41]. However, the accuracy of the arch dimensions reproduction was not measured in these studies. Several elements may affect the final accuracy of the model obtained in the 3D printing process. When preparing the data describing the virtual model to generate a physical model, it is necessary to divide it into layers. During this process, errors related to the triangulation may occur. Additionally important are the thickness of the layer of the polymerized material, the amount of polymerization shrinkage, the amount of overcuring or the properties of the light beam and the rate of exposure. The layer thickness is the fundamental factor determining the surface structure of the generated objects. The surface of the object depending on it may be more or less detailed and smooth. Final curing by irradiation with UV light and heating of the generated objects is necessary to solidify unreacted or partially reacted monomers in the 3D printing process, thus improving the mechanical properties of the object. This process can also lead to extra contraction [25].

In summary, we can say that, traditional methods proved to reproduce the dental arch and all three linear dimensions more accurately to a statistically significant degree than digital methods. The linear dimension between the molars was reproduced with the highest degree of accuracy and the dimension between the canines was reproduced with the lowest accuracy, regardless of the method used.

A limitation of the present study was its in vitro design. Another limitation was that only one IOS device was tested. A significance of this study is that the amount of publications with similar methodology, concentrating on this topic are scarce. Another important aspect of this research is the modern equipment. We were probably the first in the world to use the E3 scanner for this type of research. The development of new technologies is much faster than the pace of research.

The results of this research are in line with previous studies [17,23,31,41,42] in the statement that, in the case of more extensive reconstructions or the need to obtain maximum accuracy across the arch, traditional methods are still the gold standard. However, conventional impressions with model casting and optional digitization using extraoral scanners remain the recommended procedure [17].

## 5. Conclusions

Within the limitations of the study it can be concluded that:

1. Traditional methods using the addition silicone material provided the highest trueness of representation in the case of a full dental arch.
2. In digital methods, all analyzed linear dimensions were shortened to a statistically significantly degree compared to traditional.
3. The traditional methods provided the smallest deviations to a significant degree of linear dimensions from the pattern, and digital the largest.
4. The intercanine dimension was reproduced with the lowest accuracy, and the intermolar the highest in each method.

In spite of the fact that digital methods differ to some extent from the traditional in reproduction quality, they can be a modern alternative in diagnostic and therapeutic procedures.

**Author Contributions:** Conceptualization, M.W. and D.S.; methodology, M.W. and D.S.; software, M.W.; validation, M.W. and D.S.; formal analysis, M.W. and D.S.; investigation, M.W.; resources, M.W. and D.S.; data curation, M.W.; writing—original draft preparation, M.W.; writing—review and editing, D.S. and M.S.-N. and M.T. and R.W.; visualization, M.W.; supervision, D.S. and M.T.; project administration, M.W. and D.S.; funding acquisition, M.W. and D.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study has been supported by Medical University of Silesia research grant [KNW-2-K01/D/6/N).

**Acknowledgments:** The authors thank: Robocam and 3Shape Poland companies for free lending Trios 3 Pod intraoral scanner; Denon Dental and 3Shape Poland companies for free lending E3 extraoral scanner; Evatronix and 3D Systems Poland companies for free Geomagic Control X technical support; GCE EEO–Poland company for free GC Fujirock EP IV supply. Contents of this work are solely the responsibility of the authors and do not necessarily represent the official views of companies mentioned above.

**Conflicts of Interest:** The authors declare no conflict of interest.

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