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Article

Accuracy of Three-Dimensional Printed Dental Models Based on Ethylene Di-Methacrylate-Stereolithography (SLA) vs. Digital Light Processing (DLP)

Alexandru Vlasa [1,†], Vlad I. Bocanet [2], Mircea H. Muntean [2], Anamaria Bud [1,*], Bogdan Radu Dragomir [3,*], Sorana Nicoleta Rosu [3], Luminita Lazar [1,†] and Eugen Bud [1]

1 Faculty of Dental Medicine, University of Medicine and Pharmacy, Science and Technology George Emil Palade, 540139 Târgu-Mureș, Romania
2 Department of Industrial Engineering, Faculty of Industrial Engineering, Robotics and Production Management Machine Building, Technical University of Cluj-Napoca, 400144 Cluj-Napoca, Romania
3 Faculty of Dental Medicine, University of Medicine and Pharmacy Grigore T. Popa, 700115 Iași, Romania
* Correspondence: Anamaria.bud@umfst.ro (A.B.); Bogdan.Dragomir@umfiasi.ro (B.R.D.); Tel./Fax: +40-742825920 (A.B.); +40-744437661 (B.R.D.)
† These authors contributed equally to this work as the main author.

Abstract: Additive manufacturing is a technology that has many uses across a variety of fields. Its usage spans many fields, including the fields of art, design, architecture, engineering and medicine, including dentistry. The study aims to evaluate and compare the accuracy of three-dimensional printed dental models based on ethylene di-methacrylate using the SLA and DLP techniques. For evaluation, a reference model containing 16 maxillary permanent molars was chosen. An ATOS Capsule 3D scanner was used to scan the reference model. Using a photo-cured liquid resin, eight three-dimensional printed models were obtained using the reference model as benchmark. Four of the models (A1–A4) were obtained using SLA printing technology and four models (B1–B4) were manufactured using DLP printing technology. A standard best fit method was used to pre-align the reference and the printed model surfaces. The height of the teeth, and the mesial–distal and buccal–lingual distances were analyzed. The assessment of the two manufacturing methods was achieved by using non-parametric tests to compare the mean ranks for the assessed features. The results show that models obtained through DLP had a higher precision but also a higher bias. Both methods still are within the required accuracy range for dental models.

Keywords: three-dimensional printing; dental models; SLA; DLP

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1. Introduction

Additive manufacturing represents a manufacturing process that involves the building of an object layer by layer [1]. It is a technology that has many uses across a variety of fields. Its usage spans many fields, including the fields of art, design, architecture, engineering and medicine, including dentistry [2]. One of its main advantages is that it allows the customization of projects [3]. CAD-CAM technology has helped trigger a significant increase in the use of 3D technology in medicine and dentistry [4]. It has great potential for improving patient care, especially by improving radiologist's care. It allows radiologists to customize medicine based on acquired anatomical data [5]. Another useful area where additive manufacturing has proven useful is in the medical field, especially for training and research [6]. In the medical sector, the era of additive manufacturing is on the rise; it is mainly used in surgery to print tissues and organs, but also in the field of dental medicine to produce precise dental models (for retainers, aligners and mini-implant guides) [7], but also to directly produce the devices (from a biocompatible material) [8]. The most analyzed and studied photocurable polymers in the recent past have been poly-(ethylene glycol) diacrylate (PEGDA), poly-(ethylene glycol) di-methacrylate (PEGDMA) and poly-(propylene fumarate)/diethyl fumarate (PPF/DEF). This led to the manufacturing of tables loaded with ibuprofen, paracetamol and acetylsalicylic acid [9].

The traditional chemically activated resin-based composites form cross-links during copolymerization of methyl methacrylate and ethylene glycol di-methacrylate. The di-methacrylate monomers polymerize by means of free radical–initiated polymerization to form the organic matrix of a three-dimensional network. This highly viscous monomer can undergo free radical addition polymerization to provide a rigid cross-linked polymer. Usually, the benzoyl peroxide present in one paste acts as the initiator, whereas a tertiary amine (di-hydroxyethyl-p-toluidine) acts as the catalyst in the other paste [10].

In the near future, printing biocompatible and relatively flexible retention/lining devices may be feasible. The advantages of these techniques are accuracy, precision, speed and ease of use [10]. By using a variety of materials, it allows the creation of a complex geometric shape.

The intra-oral scanning has seen an increased use in orthodontics, leading to successful and practical use of additive manufacturing techniques. It has also shown success in the area of restorative dentistry with the use of different printing patterns. The one area where this technology has started to prove essential is implant surgery. It plays an important role in treatment and the planning of complex surgeries [11]. By using surgical guides from resins, surgery proves to be more accurate and predictable and at the same time less invasive [12]. The costs associated with additive manufacturing have become lower and the entire process is more efficient. However, there are still concerns and major impediments to their further adoption in dentistry. It is also important to highlight the need for well-trained post-processing operators that follow strict safety and health standards [13]. The 3D technology role in the area of dentistry has only scratched the surface and it is exciting to see its future applications. The world's first commercial stereolithography (SLA) printer was produced by Hull in 1988, later that year founding 3D System™. The selective sintering process (SLS) with laser was invented by Carl Deckard around the same time [14].

The two printing techniques are very different. SLA has become highly used due to its ability to produce isotropic, high-accuracy and watertight prototypes. It has become the most common printing process for resin. SLA usage is also highly associated with materials that lead to smooth surface finish [15–17]. Vat photopolymerization is mostly achieved by two manufacturing processes, SLA (discussed above) and digital light processing (DLP). The technology has gone a long way from the initial days and it has become cost-effective with small-format desktop 3D printers producing industrial-quality models at affordable prices. Both processes work by exposing liquid resin to a light source. In the case of DLP it is a projector, while in the case of SLA it is a laser. This process forms thin solid layers of plastic. The layers stack up to end up creating the solid object. Even though the two manufacturing processes are quite similar, the outputs could end up being different [18,19].

This study aims to compare and evaluate the accuracy of 3D printed dental models based on ethylene di-methacrylate using the SLA and DLP techniques.

2. Materials and Methods

For evaluation, a reference model made of Duroplastic™ containing 16 maxillary permanent molars (Frasaco™ Gmbh, Tettnang, Germany) was chosen. A GOM ATOS Capsule (Zeiss™ Gmbh, Braunschweig, Germany) was used to digitize the model. The scanning process required uncoded markers to align each exposure to the previous ones and create a 3D point cloud. According to the manufacturer, this device can measure the reference markers with a deviation of 3 µm to 5 µm. The result of the scan was a 3D polygon-mesh (Figure 1).

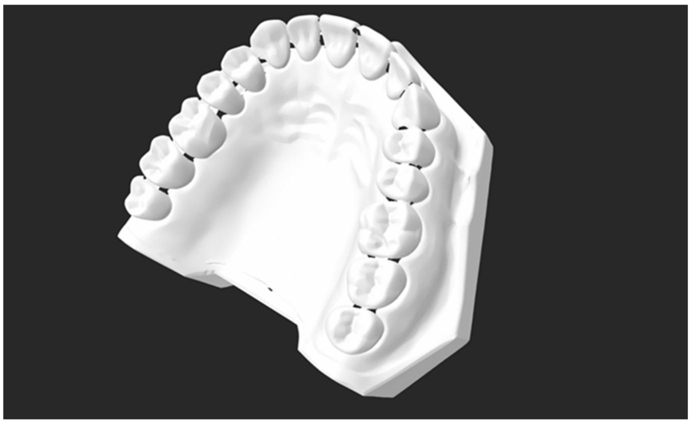

Figure 1. Three-dimensional mesh of the reference model.

2.1. Stages of Additive Manufacturing

1. Data collection was performed using the scan of the reference model as a benchmark for three-dimensional printing and comparison later in the study.
2. The analysis involved the virtual assessment of the object using a GOM Inspect 2020™ (Braunschweig, Germany) software package. After the design was loaded, the STL file was imported into the printer's software, followed by specifying the parameters for cutting and adding the support structures.
3. Printers were generally named Printer A and Printer B due to commercial reasons. Using photo-cured liquid resins (DentaMODEL™, Asiga, Sydney, Australia and NextDent™ Resin Model 2.0, Soesterberg, The Netherlands) eight three-dimensional models (Figure 2) were obtained as follows:
   - Printer A, using SLA printing technology, was used to obtain 4 three-dimensional models named Model A1, A2, A3, A4 (Figure 3A). Build volume of the pieces was 124.8 × 70.2 × 196 mm (4.9 × 2.8 × 7.7 in), with resolution 1920 × 1080 pixels, pixel pitch 65 microns (0.0025 in) (390.8 effective PPI), wavelength 405 nm.
   - Printer B, using DLP printing technology, was used to obtain 4 three-dimensional models named B1, B2, B3, B4 (Figure 3B). The maximum construction volume of the workpiece was 119 mm × 67 mm × 75 mm, resolution 1920 × 1080 pixels The printer used 385 nanometers in wavelength UV LED.

Figure 2. Typodont and 3-D printed models used in the study.

At a later stage in the study, using the GOM ATOS Capsule (Zeiss™ Gmbh, Braunschweig, Germany) scanner, the models printed previously were scanned again for comparison with the benchmark. The models were covered with an antireflexive powder to avoid any shine and so that the measurement conditions were preserved for all measurements. The results of the scanning were then exported in a STL format. A global standard best fit method was used to pre-align the reference and printed model. This minimizes the average deviations between the surfaces. A local best fit method was used to align the two surfaces in the teeth area as the global best first method aims at minimizing global deviations.

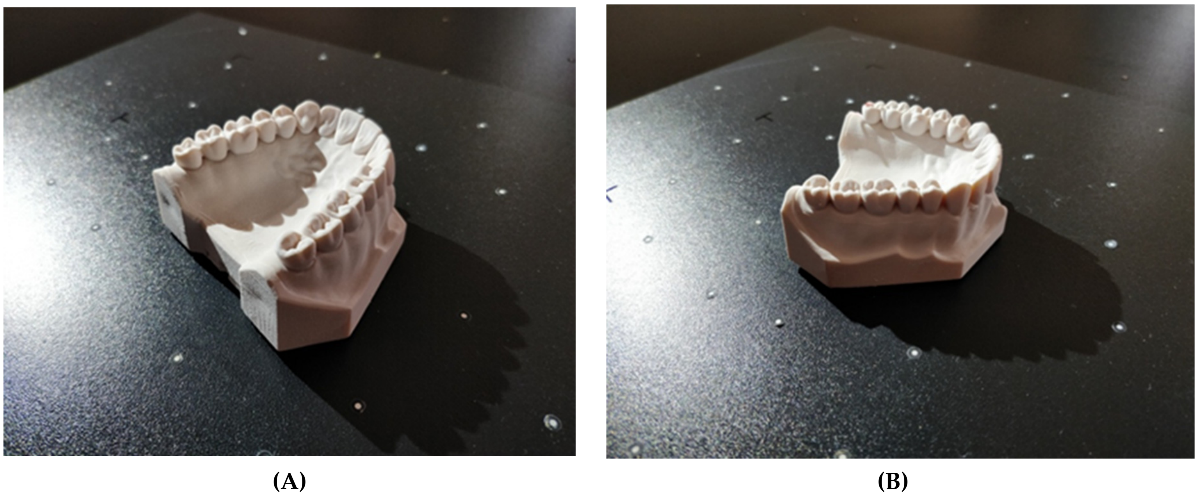

Figure 3. (**A**) Model manufactured through SLA; (**B**) Model manufactured through DLP.

The GOM Inspect 2020™ (Braunschweig, Germany) software package was used to measure and evaluate the accuracy of the models. The measurements were performed in the following incidences (schematically presented in Figure 4):

- Interdental distances of the arches, inside and outside (Figure 4A,B);
- Deviations of the medium plane buccal–lingual (Figure 4C);
- Mesial–distal dimensions (Figure 4D);
- Height of teeth (Figure 4E);
- Curvature of the arch's length (Figure 4F).

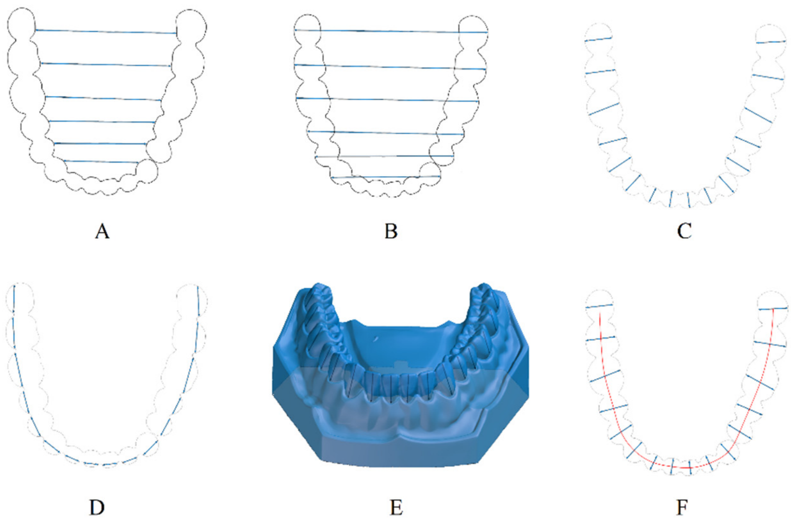

Figure 4. Schematic representation of measurement directions (features).

The width of the dental arch was obtained by measuring the inter-canine, inter-premolar and inter-molar distances on both tooth surfaces (internal and external) of each tooth. Tooth height was obtained by first calculating the distance between the gingival margin and the occlusal surface or gingival margin of each tooth. Arch curvature was determined by the mid-buccal–lingual distance of each tooth. All measurements except for the tooth height were made in a horizontal section in the median level of the tooth height.

The accuracy was evaluated by analyzing precision and bias for each feature (measurement direction). Precision is defined as a measure of how close together the measurements are, or how similar they are while bias measures how far the measurements are from the true value or reference (https://ag.arizona.edu/classes/rnr613/accuracy.html (accessed on 11 January 2023)).

2.2. Statistical Analysis

The samples distributions were tested for normality using the Kolmogorov–Smirnov and the Shapiro–Wilk test. Because the data was not normally distributed, the hypotheses were tested using non-parametric tests. As there are only two groups (printers A and B) and the data are at a ratio measurement level, the Mann–Whitney U-s test was used as a non-parametric test [20].

Visual inspection the box plots of the data for both printers and all features evaluated showed that the distributions were not similar. As a result, the mean rank of scores was evaluated instead of the median value.

3. Results

The data were first analyzed descriptively. Descriptive statistics for precision and bias for the height of the tooth, mesial–distal distance, and buccal–lingual distance are shown in Table 1. The arch curvature and interdental distances were single measurements and were omitted from the analysis. The values are expressed in millimeters.

Table 1. Descriptive analysis for precision and bias in the study group.

			The Height of the Tooth		Mesial–Distal Distance		Buccal–Lingual Distance	
			SLA	DLP	SLA	DLP	SLA	DLP
Precision (RMS)	Mean		0.016	0.020	0.042	0.023	0.031	0.026
	95% CI	Lower Bound	0.012	0.016	0.030	0.017	0.027	0.022
		Upper Bound	0.019	0.024	0.053	0.029	0.035	0.030
	5% Adjusted average		0.015	0.020	0.040	0.022	0.031	0.025
	Median		0.015	0.018	0.035	0.021	0.030	0.023
	Standard deviation		0.007	0.008	0.021	0.011	0.012	0.012
	Minimum		0.008	0.009	0.017	0.011	0.009	0.009
	Maxim		0.034	0.033	0.086	0.054	0.051	0.050
	Radius		0.026	0.024	0.069	0.044	0.042	0.042
	Interval interquartile		0.007	0.014	0.036	0.012	0.019	0.020
	Asymmetry		1.566	0.308	0.885	1.658	0.001	0.453
	Kurtoses		3.440	−1.057	−0.353	3.736	−0.799	−0.774
Bias	Mean		0.017	0.069	0.033	0.063	0.037	0.039
	95% CI	Lower Bound	0.011	0.057	0.023	0.052	0.032	0.030
		Upper Bound	0.023	0.081	0.042	0.074	0.043	0.049
	5% Adjusted average		0.017	0.069	0.033	0.062	0.037	0.037
	Median		0.013	0.074	0.034	0.058	0.036	0.036
	Standard deviation		0.012	0.023	0.017	0.020	0.017	0.029
	Minimum		0.002	0.016	0.005	0.042	0.003	0.000
	Maximum		0.036	0.112	0.060	0.107	0.067	0.136
	Radius		0.034	0.096	0.055	0.066	0.064	0.135
	Interval interquartile		0.022	0.029	0.025	0.027	0.025	0.040
	Asymmetry		0.268	−0.494	−0.055	1.025	−0.376	0.943
	Kurtoses		−1.443	1.006	−0.913	0.210	−0.618	1.717

The descriptive statistics show that SLA models show a lower average precision for tooth height, but higher values for the mesial–distal and buccal–lingual directions. Both methods show similar standard deviations for precision. On the other hand, DLP models show higher average bias than SLA models as well as a greater standard deviation of values.

Because an objective measure of significance is needed to correctly evaluate the differences between the two printing methods, statistical tests were used to determine if the differences in scores are statistically significant.

Parametric tests assume the normality of data to be reliable. The Kolmogorov–Smirnov and Shapiro–Wilk tests were used to determine if the data is normally distributed across the analyzed features (Table 2). Because the data was not normally distributed ($p > 0.05$), non-parametric tests were used, as they do not make the assumption of normality of data. The Mann–Whitney test was used to compare the two groups (SLA and DLP models).

Table 2. Normality tests for the data of the analyzed features.

			Kolmogorov–Smirnov			Shapiro–Wilk		
		Variable	**Statistic**	**df**	***p*-Value**	**Statistic**	**df**	***p*-Value**
Precision (RMS)	SLA	Height of the tooth	0.192	16	0.119	0.876	16	0.034
		Mesial–distal dist.	0.205	16	0.071	0.893	16	0.062
		Buccal–lingual dist.	0.096	41	0.200	0.969	41	0.329
	DLP	Height of the tooth	0.184	16	0.15	0.938	16	0.32
		Mesial–distal dist.	0.183	16	0.158	0.855	16	0.016
		Buccal–lingual dist.	0.11	40	0.200	0.944	40	0.047
Bias	SLA	Height of the tooth	0.16	16	0.200	0.918	16	0.159
		Mesial–distal dist.	0.104	16	0.200	0.956	16	0.587
		Buccal–lingual dist.	0.11	41	0.200	0.961	41	0.166
	DLP	Height of the tooth	0.152	16	0.200	0.965	16	0.749
		Mesial–distal dist.	0.156	16	0.200	0.881	16	0.041
		Buccal–lingual dist.	0.1	40	0.200	0.931	40	0.017

A Mann–Whitney U test was performed to identify whether there were any differences in tooth height precision and bias scores between the SLA and DLP methods (N = 32). The precision scores were statistically not significantly different between SLA (average rank = 13.94) and DLP (average rank = 19.06), U = 169, z = 1545, $p = 128$ using an exact sample distribution for U (Dineen and Blakesley, 1973) [20]. Bias scores, on the other hand, were statistically significantly lower for SLA (average rank = 8.94) compared to DLP (average ranking 24.06), U = 249, z = 4.560, $p < 0.001$.

The same tests were performed to see if there are statistically significant differences in the precision of the mesial–distal distance and between the bias scores of the methods (N = 32). The precision scores for SLA (medium rank = 21.69) were significantly higher than for DLP (average rank = 11.31), which means that DLP has a higher precision in the mesial direction than SLA, U = 45, z = −3, $p = 002$. On the other hand, SLA (average rank = 35.53) had a significantly lower bias scores than DLP (average rank = 22.88), U = 230, z = 3.844, $p < 0.001$.

In the buccal–lingual direction DLP (average rank = 35.53) had a statistically significantly lower precision score than SLA (Mean rank = 46.34), U = 601, z = 2.069, $p = 0.039$, N = 81. The bias scores between the methods (average rank A = 41.12, average rank B = 40.88) were not statistically different, U = 815, z = 0.047, z = 962.

4. Discussions

This study compared four models obtained with a DLP printing system with four SLA printed models. The measurements were obtained via extra-oral scanning. The average accuracy (precision and bias) of the two printing methods were compared.

As the data were not normally distributed, non-parametric tests were performed. The results of the comparison show that models printed with SLA (printer A) had a lower precision in the mesiodistal and buccolingual directions but similar precision in the other measured features (tooth height, arch curvature and interdental distances).

The models manufactured with the DLP method showed, on the other hand, significantly higher bias for tooth height and mesial–distal direction.

This indicates that although some methods may be more precise than others, other factors (e.g., parameter setting, model orientation along the printing axes) can influence the accuracy of the resulting models. Although models printed with DLP were more precise in certain directions, the models also showed deviations from the target values (bias).

A set of advantages that digital models offer are their ease of use for educational, diagnostic and therapeutic purposes. Digital models also have another advantage of providing much better tactile and visual information.

There are only a few studies that establish a clinically acceptable range of errors for such measurements. For clinical accuracy, the acceptable range was considered 0.20 to 0.55 mm [15]. The conclusion of our measurements based on previous study recommendations indicate that the printing models produced by DLP and SLA printers are clinically acceptable. The results indicate that the models can be viable options for various clinical applications.

In the digital dental workflow, discrepancies can be built in at every step. It is important to fully define the main characteristics evaluated in this study. The finest feature a 3D printer can reproduce is called resolution. This depends on the technology used and the printer. The three axes x, y and z are used to define the resolution (in µm). It is common to consider the layer thickness to be measured on the z axis [21]. The characteristic that represents how close two printed objects are to each other is called accuracy. Another measure that is important is the trueness. It measures the discrepancy between the desired dimensions of the object and the actual measurements [18]. The discrepancies depend also on the type of material chosen, the material activation range and its wavelength and even on the total exposure during the manufacturing of the model. Sometimes you have incompatibility between the printer and the material. Discrepancy depends also on the 3D printer that was used to manufacture the models. Each printer has its own resolution that can impact the end result. The distortion of the printed model can be influenced also by not following the recommended manufacturer's post-processing steps [17].

Given the promising potential of additive manufacturing in the area of dentistry, it is crucial to continue to analyze and evaluate the accuracy of the various 3D printed dental models.

The conclusion of our studies is that the 3D printed dental models are clinically acceptable. Measured based on accuracy, the 3D printed models are a clear positive alternative to plaster models. However, there is a difference between orthodontics and prosthodontics. A measurement difference of <300 µm between printed and orthodontic models is considered clinically acceptable [19–23]. Prosthodontics has higher accuracy needs with respect to manufactured dentures. The clinical case plays an important role in determining the additive manufacturing technology to use. The difference in accuracy needs between orthodontic and prosthodontics use cases is an important consideration. This could also be the case for other dental applications. However, the digital manufacturing technologies are already embraced by the dentistry profession. Much of laboratory work is carried out digitally, and only the final finishes are applied by hand [24–26].

Dental laboratory work takes full advantage of the CAD-CAM technology, its use becoming common place. This increase in use is also seen in dental surgery. The days of the centralized scanning are mostly behind us with many laboratories having the latest scanning technology and, in some cases, even their own milling units [25–27].

CBCT and intra-oral scanners are more common in the private practice. Both dental technicians and dentists are more capable in dealing with high volumes of digital data. From a CAD software perspective, additive manufacturing is nothing more than just another form of "output". This allows the manufacturing of complex objects and components with different type of materials.

It makes the most of its properties when the structures are unique, customized, have complicated geometry, and where 3D scan data is easy to obtain.

Additive manufacturing technology has already proved its value in dentistry, and the future holds many promises with respect to both new treatments and new manufacturing approaches to dental restorations. Nowadays, the organic biomaterials (polymers of natural origin, such as collagen, gelatin, and agarose, or synthetic in nature, such as polylactide-PLA) are used mostly for bio-printing [28]. Soft tissue regeneration can be achieved with the help of hydrogels, that can be either curable polymers (solidification leading to solid scaffolds) or soft and injectable [29]. Scaffolds allow for cell population, differentiation and adhesion to help guide tissue regeneration [4,30].

At this point, there is no guidance from national regulatory bodies with respect to the use of additive manufacturing in dentistry and surgery. It is something that will likely happen in the near future [21].

5. Conclusions

Although there are some statistically significant differences in precision and bias of different methods, additive manufacturing has proven to be a reliable option to be successfully used in the dental practice, replacing conventional models. Various additive processes are equal to or superior to established manufacturing processes and already offer considerable advantages. Additive manufacturing technology is constantly evolving, being a field that includes many branches in addition to the medical one. As technology evolves, the dentist should stay abreast of future advances that may benefit both the dentist and the patient.

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