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RESEARCH AND EDUCATION

Evaluation of the accuracy of 7 digital scanners: An in vitro analysis based on 3-dimensional comparisons

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ABSTRACT

Statement of problem. As digital impressions become more common and more digital impression systems are released onto the market, it is essential to systematically and objectively evaluate their accuracy.

Purpose. The purpose of this in vitro study was to evaluate and compare the trueness and precision of 6 intraoral scanners and 1 laboratory scanner in both sextant and complete-arch scenarios. Furthermore, time of scanning was evaluated and correlated with trueness and precision.

Material and methods. A custom complete-arch model was fabricated with a refractive index similar to that of tooth structure. Seven digital impression systems were used to scan the custom model for both posterior sextant and complete arch scenarios. Analysis was performed using 3-dimensional metrology software to measure discrepancies between the master model and experimental casts.

Results. Of the intraoral scanners, the Planscan was found to have the best trueness and precision while the 3Shape Trios was found to have the poorest for sextant scanning ($P<.001$). The order of trueness for complete arch scanning was as follows: 3Shape D800 >iTero >3Shape TRIOS 3 >Carestream 3500 >Planscan >CEREC Omnicam >CEREC Bluecam. The order of precision for complete-arch scanning was as follows: CS3500 >iTero >3Shape D800 >3Shape TRIOS 3 >CEREC Omnicam >Planscan >CEREC Bluecam. For the secondary outcome evaluating the effect time has on trueness and precision, the complete- arch scan time was highly correlated with both trueness (r=0.771) and precision (r=0.771).

Conclusions. For sextant scanning, the Planscan was found to be the most precise and true scanner. For complete-arch scanning, the 3Shape Trios was found to have the best balance of speed and accuracy. (J Prosthet Dent 2016;■:■-■)

Intraoral digital impression making has evolved beyond single tooth preparations and sextant scanning to include the ability to record complete arches. Intraoral digital scanners allow the dentist to capture the surface of the teeth, implant scanbodies, and soft tissues in 3 dimensions, enabling instant evaluation of the digital cast and near instant communication to the laboratory, 3-dimensional (3D) printer, or chairside milling unit. Similarly, computer-aided design and computer-aided manufacturing (CAD-CAM) has revolutionized the way dentistry is practiced and has become integrated into patient care.[1,2] Recent advances in chairside and laboratory digital technology have cultivated an enhanced environment for the widespread use of digital dentistry.[1,2]

Two events that have increased the acceptance of digital technology are the emergence of newer and more user friendly intraoral digital scanners and the adoption of digital technology into dental school curricula.[3] Deficiencies with elastomeric impression materials and techniques have been documented to support the need for new and better impression techniques.[4-8] Commonly reported weaknesses of elastomeric impression materials

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Clinical Implications

Intraoral scanners are remarkably accurate; nevertheless, each scanner has unique strengths and weaknesses that should be considered, in that no one scanner proved to have the best combination of accuracy and speed.

include technique sensitivity, patient discomfort, dimensional changes after polymerization, tray distortion, dental stone distortion, and distortion from disinfection agents.[9-20] Despite these minor shortcomings, the combination of elastomeric impression materials and dental stone casts has been successful over a long period.[10]

Clinicians seeking to overcome the shortcomings of conventional elastomeric impressions have implemented digital impressions as an adjunct or replacement for elastomeric impression materials. One advantage gained from digital impression technology is the ability to use digital magnification and quality control tools to highlight defective areas and provide guidance on how to capture missing areas of the digital impression.[21] This enables immediate identification of defects, and the clinician can rescan those areas without having to remake the entire impression.[21] However, digital impressions also have disadvantages, and, when compared with elastomeric impressions, the potential exists for greater distortion of the digital impression, possibly due to poor technique or the limitations of the specific scanning technology.[22]

Accuracy consists of precision and trueness (ISO 5725-1).[23] Precision (Fig. 1) describes how close repeated measurements are to each other.[22] Therefore, a scanner with higher precision correlates to a more repeatable and consistent scan.[22] Trueness (Fig. 1) describes how far the measurement deviates from the actual dimensions of the measured object.[22] Therefore, a scanner with high trueness indicates that the scanner delivers a result that is close or equal to the actual dimensions of the object being scanned.[22] Ender et al[22] found that for complete-arch treatments, conventional impressions were significantly more accurate than digital impressions. Furthermore Flügge et al[24] found the precision of intraoral scanners decreased with an increasing distance between the scanbodies.

Unfortunately, many accuracy studies have limited clinical value because they evaluated a single tooth, reporting accuracy data that may not apply to more complicated clinical situations.[25,26] For example, Hack et al[25] found excellent trueness values were obtained using intraoral digital scanners when evaluating a single tooth scan as follows (in order of trueness): 3Shape TRIOS

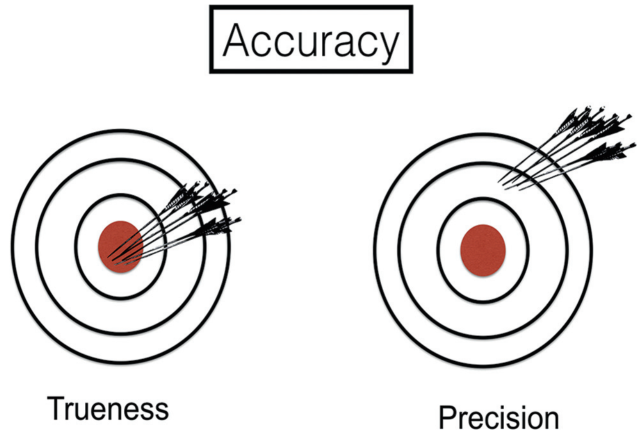

Figure 1. Components of accuracy explained graphically.

(6.9 ±0.9 μm), Carestream 3500 (9.8 ±0.8 μm), iTero (9.8 ±2.5 μm), True Definition (10.3 ±0.9 μm), Planscan (30.9 ±10.8 μm), and CEREC Omnicam (45.2 ±17.1 μm). Several studies scanned metal or polymeric materials with a refractive index (RI) that was different from the RI of tooth structure. These studies may not provide reliable information on the accuracy of a scanner designed to be used intraorally.[25-28] Nedelcu and Persson[26] found that the type of material being scanned has a significant impact on the accuracy of the scanner. Su and Sun[28] found that the larger and more complicated the scan area, the lower the accuracy. Therefore, it is difficult to compare individual studies directly in order to arrive at a general conclusion regarding the accuracy of intraoral scanners.

This study was designed to address some of these concerns. The primary purpose was to evaluate the 2 components of accuracy, trueness and precision (Fig. 1), of 7 digital scanning systems. These systems were used to scan sextants and complete arches using a master model composed of a material with an RI similar to tooth structure. The secondary purpose was to record the scanning times to determine if a relationship exists between speed and accuracy and precision. The null hypothesis was that no differences would be found between the various scanners regarding accuracy and precision in sextant and complete-arch scanning and that scanning time is not related to the accuracy and precision of the scanners.

MATERIAL AND METHODS

Seven digital impressions systems were evaluated: CEREC Omnicam (CO) (Dentsply Sirona), CEREC Bluecam (CB) (Dentsply Sirona), Planmeca Planscan (PS) (Planmeca USA), Cadent iTero (IT) (Align Technology), Carestream 3500 (CS) (Carestream Dental), 3Shape TRIOS 3 (ST) (3Shape North America), and 3Shape D800 model scanner (SD) (3Shape North America).

The CO is a powder-free, color video speed scanning system. It uses active triangulation and emits white light to measure surfaces,[25] and is based on video technology that captures the anatomy and color of the oral tissues with a broad focal depth camera.[29] The CB uses a blue light-emitting diode to take single images on surfaces powdered with titanium dioxide that is necessary for capturing the surface anatomy.[30] As opposed to the other systems, the CB and the CO are closed in that open stereolithography (STL) files are not natively available without additional cost, thus limiting use of these images. The PS uses blue laser technology with wavelengths of 450 nm during its video speed scanning. Its wand requires smooth movement while allowing the tip to move over the tooth surface.[25] This system is open, which means it allows free STL cast import and export. The CS is designed as a single image system where the camera automatically makes an image when steadily held at the correct focal depth, allowing the scanner to have good precision (4.5 ±0.8 μm) and trueness (9.8 ±0.8 μm) for single-tooth typodont tooth scans.[25] The IT scanner uses a proven parallel confocal imaging technology with red laser light beams to capture images of dental tissues.[25,29-33] The ST scanner is based on confocal microscopy capturing multiple images in a very short time. Its wand needs to be positioned over the structures to be captured.[25,29,31] The SD extraoral scanner has been reported to have a precision of less than 20 μm with an image resolution of the built-in camera of 5 megapixels for texture mapping.[28]

Measuring the accuracy of the definitive cast created by conventional elastomeric impression techniques is typically done by line distance with limited points, according to studies based on ISO 4823.[13,34,35] However, evaluation of the accuracy of digital impressions is treated differently and has been reported in the literature to be accurately analyzed with sophisticated 3D software. This software uses best-fit mathematical algorithms to overlay a digital impression on a digital master to objectively measure variances across the entire experimental model in relation to the master (Fig. 2).[22-28]

A sextant and a complete-arch digital impression were made of a custom model using the dental scanners, and the accuracy and precision were evaluated and compared using a master scan as the reference model. A custom master model was fabricated in the following manner. Fourteen maxillary typodont teeth (Model D85SDP-200; Nissin Dental Products Inc) were placed in a dentiform (Kilgore International Inc) and prepared for complete coverage ceramic crowns in accordance with the principles of Rosenstiel et al[36] with the following specifications: a smooth continuous 1-mm modified shoulder finish line that followed the rise and fall of the gingiva, 6 to 10 degrees combined convergence angle, a functional cusp bevel, 1.5 to 2 mm of occlusal reduction, 1

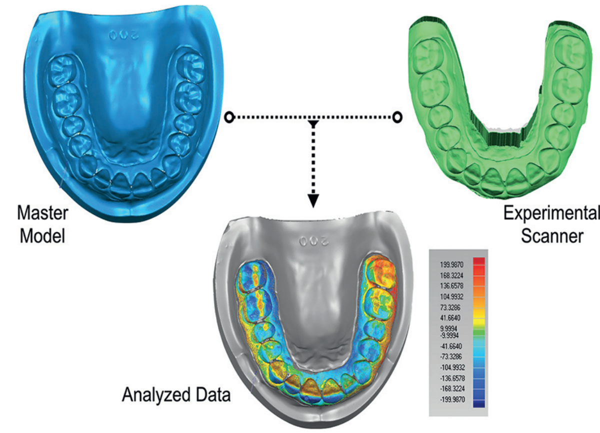

Figure 2. Simplified graphic representation of analysis done by Geomagic Control software.

to 1.5 mm of axial reduction, and an overall rounded and smooth finish. Telio CAD (TC) polymethyl methacrylate (shade A3; Ivoclar Vivadent US) restorations were fabricated and bonded onto the typodont after airborne-particle abrasion of the intaglio surfaces of the restorations with (40 μm coJet sand; 3M ESPE). They were then cemented to the typodont with self-etching, self-adhesive resin cement (Rely-X Unicem; 3M ESPE).[37] The TC material was chosen to simulate tooth substance because its RI (1.49) is within the range of enamel (1.63) and dentin (1.54).[26,38] A master reference scan of the model was obtained from an industrial 3D scanning company (Capture 3D). The reference model was created with an ATOS Triple Scan (GOM Technologies), an industrial structured blue light 3D scanner. This scanner has been shown to be accurate to 3 μm and demonstrates repeatability of 2 μm for jaw-sized scans.[39] Next, 5 complete arch digital impressions and 5 sextant digital impressions were made by clinicians with experience using the impression systems. Six different dental intraoral scanners and 1 model scanner were used. A sample size of 5 for each category was determined using a priori power analysis based on a pilot study. Each scanner was calibrated using the manufacturer's calibration guidelines. In the case of the PS, which does not come with a calibrating device, the company sent a calibration device. Each data set was converted to an STL file using the appropriate manufacturer's recommended conversion. The STL files were then compared with the master STL file using a 3D analysis software program (Geomagic Control; 3D Systems) (Fig. 2). This software aligned the scans with the master scan made with the ATOS Triple scan using a best fit algorithm. Average maximum and minimum values were displayed in the software and were recorded along with standard deviation for each scan. During the scanning, a separate operator recorded the time taken with a digital stopwatch, and all times were averaged.

Table 1. Raw data (μm) used for statistical analysis on various scanners for sextants

Scanner	Location	N	Mean	Median	SD	Minimum	Maximum
Cerec Bluecam	Lower	5	54.6	56.00	5.37	48.0	62.0
	Upper	5	60.4	59.00	8.68	50.0	73.0
Carestream 3500	Lower	5	65.2	64.00	2.39	63.0	69.0
	Upper	5	72.4	71.00	6.91	66.0	83.0
Cerec Omnicam	Lower	5	63.6	62.00	5.81	59.0	73.0
	Upper	5	48.8	46.00	5.59	44.0	58.0
iTero	Lower	5	58.8	59.00	4.97	52.0	66.0
	Upper	5	56.2	55.00	6.57	49.0	63.0
Planscan	Lower	5	51.2	51.00	2.49	48.0	55.0
	Upper	5	45.6	46.00	3.21	42.0	50.0
3Shape TRIOS 3	Lower	5	72.0	70.00	7.91	62.0	81.0
	Upper	5	65.2	58.00	18.94	41.0	85.0
3Shape D800	Lower	5	53.0	53.00	2.74	50.0	57.0
	Upper	5	46.8	45.00	4.27	42.0	53.0

Table 3. Raw data used for statistical analysis on sextant precision (μm)

Scanner	N	Mean	Median	SD	Minimum	Maximum
CEREC Bluecam	5	89.6	90.0	6.35	82.0	98.0
Carestream 3500	5	97.0	97.0	4.90	93.0	105.0
CEREC Omnicam	5	89.8	89.0	4.92	86.0	98.0
iTero	5	84.6	85.0	4.51	79.0	91.0
Planscan	5	79.8	81.0	5.17	71.0	84.0
3Shape TRIOS 3	5	98.0	94.0	9.51	87.0	108.0
3Shape D800	5	79.0	79.0	2.74	76.0	83.0

For trueness, a linear mixed model was used to analyze average deviation, with location (upper and lower end deviations), type of scanner, and their interaction as covariates. A random intercept was in the model to account for replicates. To analyze the precision, a 1-way analysis of variance model with a random intercept was used. For the post hoc pairwise comparisons, the Scheffé adjustment was applied (α=.05 for all comparisons, except for post hoc comparisons, where the Scheffé method was applied to account for the number of comparisons being made. To evaluate correlations between precision and trueness and scan times, Spearman correlations were used. A relationship was considered strong between time and precision or trueness if the correlation value was greater than 0.7.

RESULTS

Summary statistics for sextant trueness (for each location, lower and upper end deviations) are presented in terms of mean, median, standard deviation, minimum, and maximum in Table 1. The interaction effect between location and scanner for trueness was found to be significant (*P*=.009), as was location (*P*=.047) and scanner (*P*<.001). That is, significant differences were found in the type of scanner between the lower and upper end micrometer deviations. The significant post hoc comparisons for the interaction term and for scanner type

Table 2. Significant differences in sextant trueness (μm)

Scanner	Mean Trueness	Scanner	Mean Trueness	*P*
Planscan	48.4	Carestream 3500	68.6	<.001
Shape D800	49.9	Carestream 3500	68.6	<.001
Planscan	48.4	3Shape TRIOS 3	68.8	<.001
3Shape D800	49.9	3Shape TRIOS 3	68.8	<.001
CEREC Omnicam	56.2	Carestream 3500	68.6	.016
CEREC Omnicam	56.2	3Shape TRIOS 3	68.8	.019
Cerec Bluecam	57.5	Carestream 3500	68.6	.045
iTero	57.5	Carestream 3500	68.6	.045

Scanner with higher trueness on left.

Table 4. Significant differences in sextant precision (μm)

Scanner	Mean Precision	Scanner	Mean Precision	*P*
iTero	84.6	Carestream 3500	97.0	<.001
Planscan	79.8	Carestream 3500	97.0	<.001
3Shape D800	79.0	Carestream 3500	97.0	<.001
iTero	84.6	3Shape TRIOS 3	98.0	<.001
Planscan	79.8	3Shape TRIOS 3	98.0	<.001
3Shape D800	79.0	3Shape TRIOS 3	98.0	<.001
3Shape D800	79.0	CEREC Omnicam	89.8	<.001
3Shape D800	79.0	CEREC Bluecam	89.6	<.001
Planscan	79.8	CEREC Omnicam	89.8	.002
Planscan	79.8	CEREC Bluecam	89.6	.002
CEREC Bluecam	89.6	3Shape TRIOS 3	98.0	.015
CEREC Omnicam	89.8	3Shape TRIOS 3	98.0	.019

Scanner with higher precision on left.

Table 5. Raw data used for statistical analysis on complete-arch trueness (μm)

Scanner	Location	N	Mean	Median	SD	Minimum	Maximum
Carestream 3500	Lower	5	75.0	77.0	5.70	68.0	81.0
	Upper	5	77.0	77.0	6.52	69.0	86.0
CEREC Omnicam	Lower	5	107.6	105.0	13.46	92.0	127.0
	Upper	5	95.4	96.0	10.76	84.0	110.0
CEREC Bluecam	Lower	5	125.4	100.0	62.48	62.0	220.0
	Upper	5	155.6	115.0	74.63	83.0	250.0
iTero	Lower	5	60.0	59.0	4.85	54.0	67.0
	Upper	5	52.4	52.0	2.70	49.0	56.0
3Shape D800	Lower	5	41.6	41.0	2.41	39.0	45.0
	Upper	5	45.6	45.0	2.70	43.0	50.0
Planscan	Lower	5	89.4	80.0	27.08	65.0	130.0
	Upper	5	103.0	90.0	44.67	61.0	166.0
3Shape TRIOS 3	Lower	5	69.6	73.0	10.64	56.0	83.0
	Upper	5	69.2	73.0	7.56	61.0	76.0

(using the Scheffé adjustment) are presented in the Table 2. The raw data are presented in Table 1. After analysis, they indicated that the order of trueness when sextants were scanned from most true to least is as follows: PS>SD>CO>IT>CB>CS>ST. Significant differences are presented in Table 2.

Summary statistics for precision (for each location, lower and upper end deviations) are presented in terms of mean, median, standard deviation, minimum, and maximum in Table 3. The linear mixed model analysis of the standard deviation suggests strong statistical

Table 6. Significant differences in complete-arch trueness (μm)

Scanner	Mean Trueness	Scanner	Mean Trueness	*P*
iTero	56.2	CEREC Bluecam	140.5	<.001
3Shape D800	43.6	CEREC Bluecam	140.5	<.001
3Shape TRIOS 3	69.4	CEREC Bluecam	140.5	.001
Carestream 3500	76.0	CEREC Bluecam	140.5	<.001
3Shape D800	43.6	CEREC Omnicam	101.5	.009
3Shape D800	43.6	Planscan	96.2	.024

Scanner with higher trueness on left.

Table 8. Significant differences in complete-arch precision (μm)

Scanner	Mean Precision	Scanner	Mean Precision	*P*
3Shape D800	69.2	CEREC Bluecam	194.2	.010
iTero	89.4	CEREC Bluecam	194.2	.046

Scanner with higher trueness on left.

evidence to support a significant difference ($P<.001$) among scanner types with regard to precision (Table 4). The post hoc comparisons are presented in Table 4. The raw data are presented in Table 3, and significant differences in Table 4. The order of most precise to least is as follows: SD>PS>IT>CB>CO>CS>ST.

The interaction effect in the linear mixed effects model analysis for trueness was not found to be significant ($P<.8$). That is, the differences in the types of scanner were similar in the lower and upper micrometer deviations. Therefore, the analysis was repeated without the interaction to compare the scanner types (adjusting for the location). The raw data for complete-arch trueness are presented in Table 5, and the scanner types were found to be significantly different ($P<.001$). The post hoc comparisons between the scanner types are presented in Tables 5 and 6. The results indicate that the order of trueness when complete arches were scanned are as follows: SD>IT>ST>CS>PS>CO>CB. Significant differences are highlighted in Table 6.

The linear mixed model analysis of the standard deviation shows statistical evidence ($P<.001$) to support a difference between scanner types. The raw data for complete-arch precision are presented in Table 7, and the post hoc comparisons in Table 8. The order of most precise to least precise with complete-arch scanning is as follows: SD>IT>ST>CS>PS>CO>CB. Significant differences are presented in Table 8.

Scan times are presented in Table 9. The correlation of scan time, trueness, and precision were analyzed using Spearman correlations. Precision and trueness were highly correlated with complete-arch scan time (r=0.771). The rest of the scan times were moderately or not correlated with precision.

DISCUSSION

The null hypothesis was partially rejected, in that significant differences were found among some of the digital impression systems regarding trueness and precision. For scanning time, the null hypothesis was not rejected for all relationships, except for the complete-arch total time (with render). In this instance a strong correlation was found with time and trueness and precision.

Table 7. Raw data used for statistical analysis on complete arch precision (μm)

Scanner	N	Mean	Median	SD	Minimum	Maximum
Carestream 3500	5	113.8	114.0	2.39	111.0	117.0
CEREC Omnicam	5	133.4	137.0	9.71	121.0	145.0
CEREC Bluecam	5	194.2	136.0	98.38	105.0	333.0
iTero	5	89.4	88.0	2.88	87.0	93.0
3Shape D800	5	69.2	69.0	3.27	66.0	73.0
Planscan	5	124.6	108.0	51.52	78.0	197.0
3Shape TRIOS 3	5	105.6	107.0	6.47	96.0	113.0

Table 9. Scan times (minutes:seconds) for sextants and complete arch with and without rendering times

Scanner	Sextant Scan Time	Sextant Total Time (With Render)	Complete Arch Scan Time	Complete Arch Total Time (With Render)
CEREC Omnicam	0:15	0:48	0:47	2:04
3Shape Trios 3	0:32	0:34	2:10	2:30
Planscan	0:47	0:53	2:45	3:18
CEREC Bluecam	0:23	0:45	1:40	3:08
Carestream 3500	0:50	1:42	4:44	6:00
iTero	2:30	3:02	6:04	6:44

Despite modeling several variables, this study did not replicate an actual clinical situation and has several limitations. In most patients, multiple substrates are scanned, including amalgam, ceramic, cast metal, composite resin, dentin, enamel, and soft tissues. Further studies should be done to determine whether these different materials affect accuracy. To minimize the risk of operator bias and experience influencing the results, only investigators experienced with each system were used. Therefore, this study failed to look at how operator experience influences accuracy, because all operators were very experienced with the given system. A new user can create less than ideal results.[40] Lastly, this study failed to account for saliva, soft tissue isolation, patient movement, and humidity in the oral environment as well as the laboratory procedures after scanning, which may compound errors in the restoration fabrication process. These patient variables may considerably affect accuracy in a clinical situation.

Although a direct comparison with published results is difficult because of variations in study design, the results of this study are in agreement with values reported in the literature for trueness and precision of intraoral impression systems.[22-33] Hack et al[25] found the ST to be the truest scanner when evaluating a single tooth. In contrast, this study found the PS was the most true for sextants. The discrepancy in results between this study and that of Hack et al may be due to different materials being scanned, different software versions being used, different numbers of teeth being analyzed, or different analysis software being used.

The SD had the best accuracy for complete-arch scanning. The CS and the IT were the 2 intraoral scanners that performed the best for complete arches but were also the slowest. Therefore, there was a strong correlation with scan time (with render) for complete-arch scanning and trueness and precision. Rendering times should be factored in as this is the time it takes a system to fabricate a digital model from the impression. The system that had the best combination of speed, trueness, and precision for complete-arch scanning was the ST. This system was the most accurate of the video speed systems for dealing with complete-arch scanning and was also noted as being fast and straightforward to use.

Further research is needed, and a standardized method needs to be developed to evaluate and compare multiple intraoral impression systems. Because accounting for software versions, scanning substrate variability, and arch configurations is difficult, the results of this paper should be interpreted with caution; conclusions can only be drawn for the exact scanning scenario outlined in this paper.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Scanners differ regarding the speed, trueness, and precision of sextant scans, with the Planscan and the CEREC Omnicam providing the best combination of speed, trueness, and precision.
2. Scanners differ regarding the speed, trueness, and precision of complete-arch scans, with the 3Shape TRIOS 3 providing the best combination of speed, trueness, and precision.

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