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Scanning of a Dental Implant with a High-Frequency Ultrasound Scanner: A Pilot Study

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Abstract: The purpose of this in vitro study was to assess the trueness of a dental implant scanned using an intraoral high-frequency ultrasound prototype and compared with conventional optical scanners. An acrylic resin cast containing a dental implant at position 11 was scanned with a fringe projection 3D sensor for use as a reference dataset. The same cast was scanned 10 times for each group. Ultrasound scanning was performed with a high-frequency probe (42 MHz, aperture diameter of 4 mm and focus length of 8 mm), and 3D images were reconstructed based on the depth of each surface point echo. Optical scans were performed in a laboratory and with an intraoral scanner. A region of interest consisting of the dental implant site was segmented and matched to the reference dataset. Trueness was defined as the closeness between experimental data and the reference surface. Statistical analysis was performed with one-way ANOVA and post-hoc tests with a significance level of $p = 0.05$. No statistical difference was found among the evaluated scanners. The mean deviation error was 57.40 ± 17.44 μm for the ultrasound scanner, 75.40 ± 41.43 μm for the laboratory scanner and 38.55 ± 24.34 μm for the intraoral scanner. The high-frequency ultrasound scanner showed similar trueness to optical scanners for digital implant impression.

Keywords: dental impression technique; dental implants; ultrasonography

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1. Introduction

An accurate implant impression and an adequate working cast are important steps in avoiding mechanical and biological complications of dental-implant-supported prostheses [1–4]. However, a conventional workflow is susceptible to errors that can result in the displacement of implant components and subsequent inaccuracy in the reproduction of the three-dimensional (3D) implant position [5]. By using computer aided design/computer aided manufacturing (CAD/CAM) technology, clinical and laboratory procedures are reduced. Thus, potential inaccuracies related to a conventional workflow are avoided [6,7].

The first step in a digital workflow is the acquisition of virtual data by means of intraoral or laboratory scanning [8]. For this purpose, different optical technologies are used, such as photogrammetry, triangulation, confocal imaging, or active wavefront sampling [9]. In general, the principle of image acquisition is the overlapping of multiple acquired images, creating a three-dimensional representation of the scanned object.

Final surface reconstruction accuracy depends on several steps related to the image acquisition and processing procedures [10]. Whereas scanner devices differ in their capture mode and image reconstruction, the operator experience and scanning protocol also affect the accuracy of digital data [11,12]. Clinical conditions, such as the presence of saliva and blood, may make it difficult to acquire data, when intraoral scanners are used [13].

Previous studies have recommended the use of ultrasound to scan dental implants and surrounding tissues [14–19]. Recently, a high-frequency ultrasound-based scanner was introduced for scanning teeth [19–22]. According to Marotti et al. (2019), the mean deviation value of ultrasound images ranged from 12.34 to 46.38 µm, and its accuracy was comparable with that obtained by commercially available optical scanners.

Clinically, it is frequently necessary to scan prepared teeth and dental implants at the same time. However, to date, no study has been conducted on the possibility of using ultrasound for scanning the dental implant. Therefore, this preliminary pilot study showed the digitalization of dental implants scanned with a new ultrasound-based intraoral scanner prototype. Trueness of the ultrasound scanner in comparison with commercially available optical scanners was assessed.

2. Materials and Methods

An acrylic resin model, containing three dental implants at the maxillary edentulous sites (central incisor, first premolar and first molar), was prepared and used as the master model. However, for this pilot study, measurements were taken only from the dental implant placed at the site of a maxillary right central incisor (position 11).

In summary, model preparation consisted of implant perforations made with a micro-milling machine (M7HP, Datron Dynamics, Mühltal, Germany), which ensured the placement of dental implants (bone level 4.1 × 10 mm, Straumann) with the desired angulation (position 11 at 90°). A scan body (Straumann CARES) was fixed over the dental implant, and a digital model was acquired by scanning the master cast with a fringe projection 3D sensor (COMET 5 11Ma, Carl-Zeiss, Oberkochen, Germany). The digital model was used as a reference dataset and represented the true values of the implant position (Figure 1).

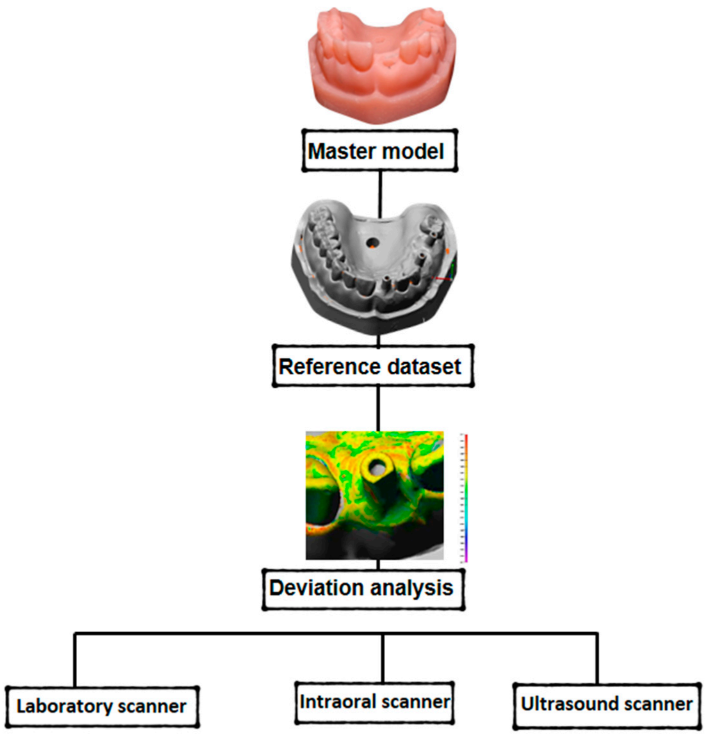

Figure 1. Representation of methodology used in this study. Acrylic-resin cast containing dental implants was digitized for use as reference data set. The scan was performed with ultrasound, laboratory scanner and intraoral scanner. Measurement error was calculated as deviation between scanned cast compared with reference dataset.

The same acrylic resin model was scanned with ultrasound, laboratory and intraoral scanners (10 scans for each group). All scans were performed by the same calibrated operator using the protocol described below.

2.1. Ultrasound

Ultrasound scans were performed with a high-frequency ultrasound intraoral prototype, developed at the Department of Medical Engineering, Helmholtz Institute, RWTH Aachen University, Germany (Figure 2). The concept and development of the scanner were previously described [14]. Herein, a pilot study was conducted to assess the scanner's viability to digitally reproduce the dental implant installed in a dental arch.

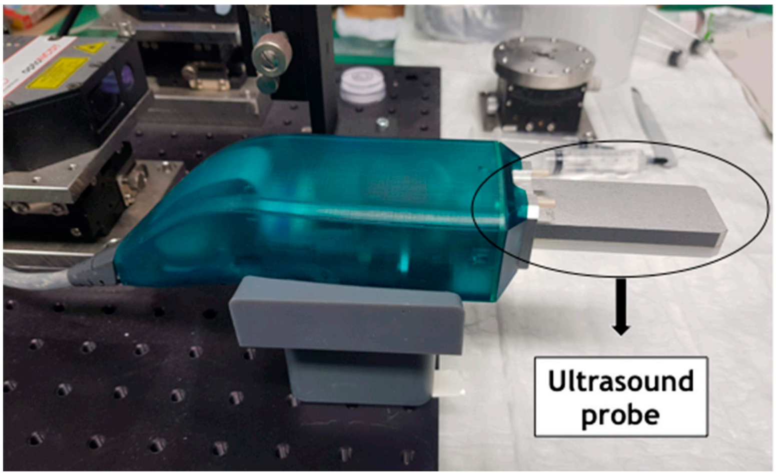

Figure 2. High-frequency intraoral ultrasound scanner used in this study. Prototype showing the ultrasound probe.

An individual partial tray covering 3–5 teeth was especially designed to allow the acoustic coupling and stabilization of the ultrasound scanner during the scanning process. Through a perforation at the vestibular site, the inner part of the tray was filled with ultrasound gel (Sonogel, Sonogel Vertriebs GmbH, Bad Camberg, Germany) to allow the acoustic coupling. Stabilization of the ultrasound probe during the scanning process was ensured by placing it on an occlusal table with exactly the same dimension as the probe over the tray.

First, the tray was filled with silicon material; then, it was placed on the dental arch to take an impression of the teeth adjacent to the dental implant. This step was taken to ensure stabilization of the tray over the dental arch. Excessive material was removed from dental implant site, and this was carefully filled with ultrasound gel. Special care was taken to avoid bubble formation, by using an irrigation syringe.

The high-frequency ultrasound scanner used in this study consisted of a single-element transducer with frequency of 42 MHz, aperture diameter of 4 mm and focus length of 8 mm. This was mechanically driven using a two-degree-of-freedom mechanism. A pulser/receiver (Imaginant Inc., Pittsford, NY, USA) with a bandwidth of 150 MHz and an analogue-to-digital-converter (GaGe EON CompuScope CS122 G1, Dynamic Signals LLC, Lockport, NY, USA) with a sampling rate of 500 MHz, and 12-bit resolution, was coupled to the system. B-mode images were converted to 3D datasets using algorithms developed at the Department of Medical Engineering. A 3D point cloud representing the scan body and tooth surfaces was generated based on the depth of echo of each surface point.

2.2. Laboratory Scanner

Laboratory digitization was performed with an optical laboratory scanner (CARES Scan CS2, Straumann, Basel, Switzerland). Prior to the scanning, the master cast was powdered and fixed into the scanner platform. During scanning, the platform moves, allowing laser contact at different angles of the cast.

2.3. Intraoral Scanner

Lava COS (Lava Chairside Oral Scanner; 3M ESPE, St. Paul, MN, USA) was used for intraoral scanning. Likewise, a thin layer of powder (Lava Powder, 3M ESPE, St. Paul, MN, USA) was applied on the surface of the master cast. A full-arch scan was performed according to the manufacturer's instructions.

2.4. Measurement Analysis

Digital data were analyzed with the software Cloud Compare 2.6.1. The region of interest encompassed the dental implant site that was limited by the midline of adjacent teeth (Figure 3). In order to assess trueness, each dataset was superimposed to the reference dataset through a combination of manual and automatic registration (Figure 4).

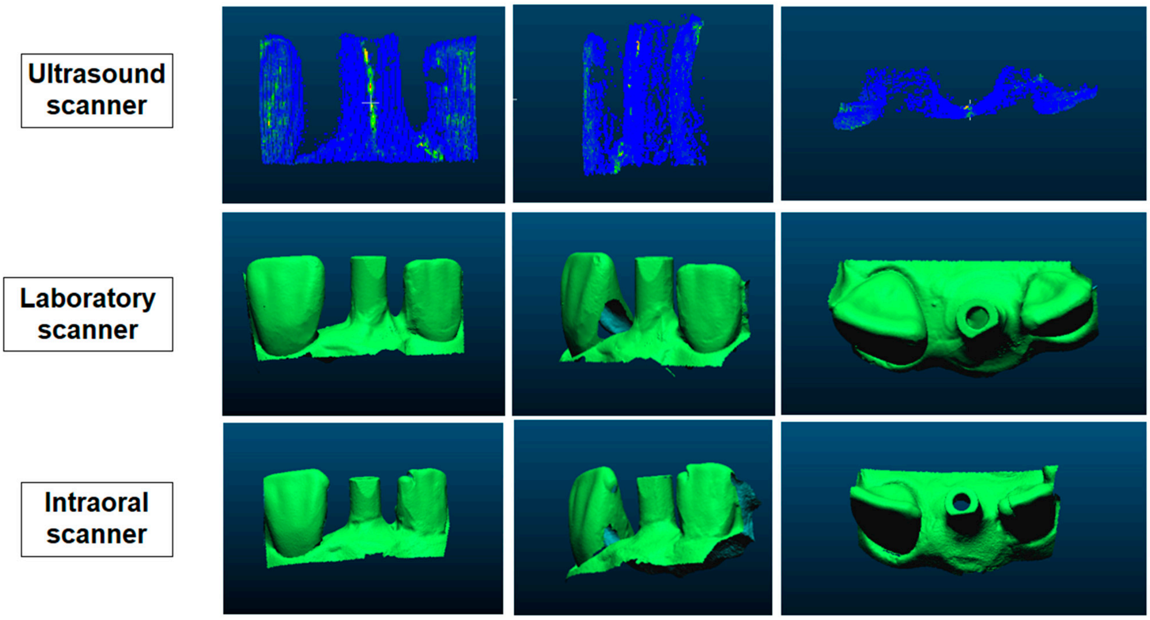

Figure 3. Digital data acquired with ultrasound (ASCII file), laboratory and intraoral (standard tessellation language files) scanners.

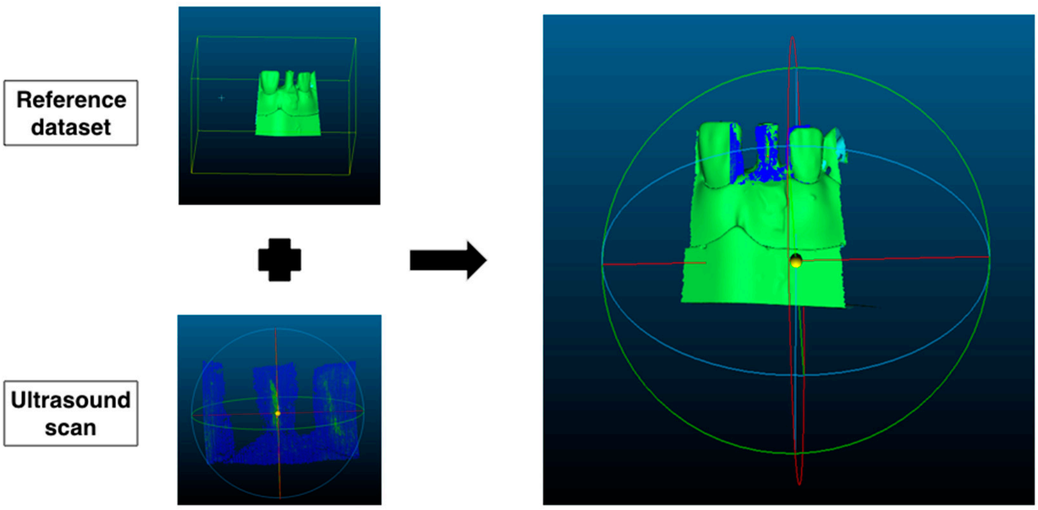

Figure 4. Test and reference datasets were aligned using manual and automatic methods to determine the closest common points. Manual alignment was performed by determining equivalent data points between data.

Trueness was defined as the closeness between the experimental and reference data sets (Figure 5) assessed by the discrepancy between them, which was automatically calculated by the software.

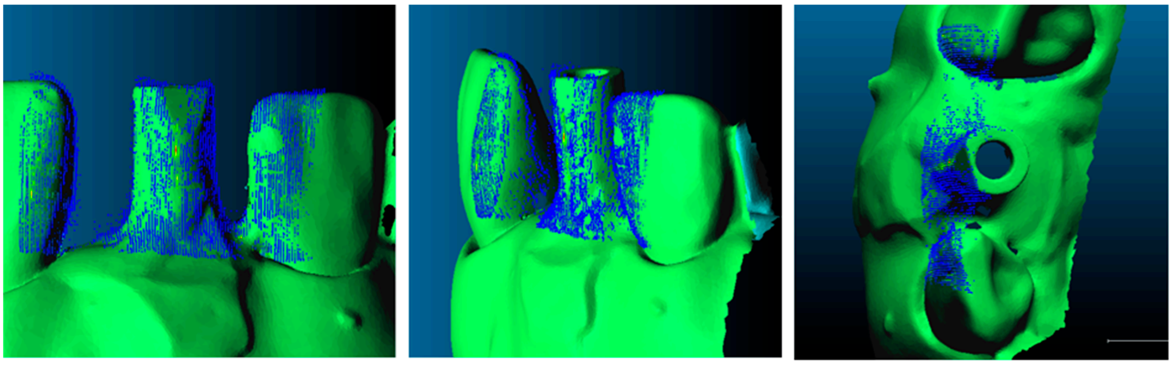

Figure 5. Alignment of ultrasound scans (blue) with the reference dataset (green).

2.5. Statistical Analysis

Statistical analysis was performed using the software SPSS 22.0. Adherence to normality was assessed with the Shapiro–Wilk test, and data were described as mean and standard deviation. The difference in values among trueness of ultrasound and optical scanners was assessed by ANOVA and post-hoc tests with a significance level of $p = 0.05$.

3. Results

The mean discrepancy value was higher for the laboratory scanner (75.40 $\pm$ 41.43 µm), followed by the ultrasound (57.40 $\pm$ 17.44 µm) and intraoral scanners (38.55 $\pm$ 24.34 µm). However, no statistically significant difference was found among scanners (Table 1), suggesting the potential of ultrasound to be used clinically. Maximal discrepancy was 2.09 $\pm$ 0.54 mm for the laboratory scanner, 2.06 $\pm$ 0.54 mm for the ultrasound scanner and 1.86 $\pm$ 0.51 mm for the intraoral scanner (Figure 6).

Table 1. One-way repeated measures ANOVA.

	Source	Sum of Squares	Df	Mean Square	F	*p*-Value
Sphericity assumed	Scanner	6790.81	2	3395.40	3.17	0.06
	Error	19,224.91	18	1068.051	-	-

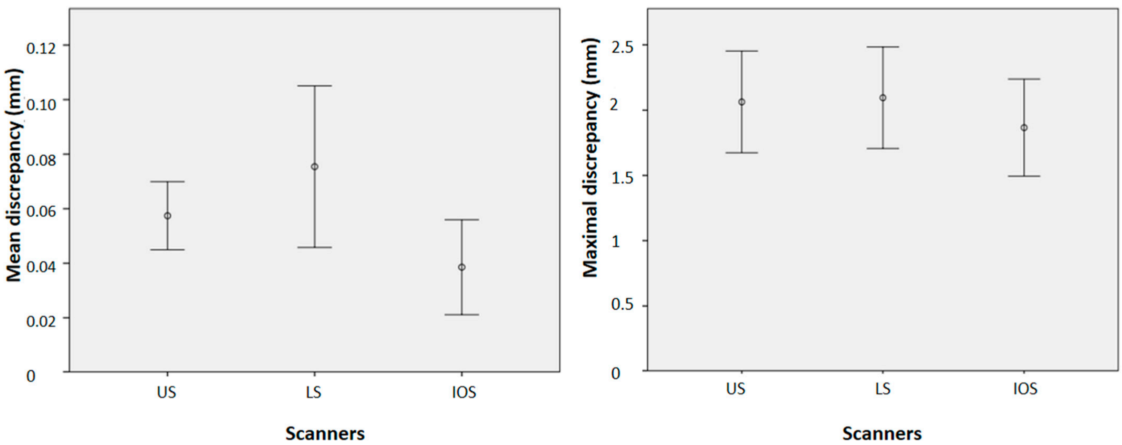

Figure 6. Mean and maximal discrepancy values obtained by ultrasound (US), laboratory scanner (LS) and intraoral scanner (IOS). No statistically significant difference was found between the scanners for the mean and maximal discrepancy values.

4. Discussion

The ultrasound scanner showed trueness that was comparable with that of the commercial optical techniques used for taking impressions of an implant at tooth position 11. True values showed that the implant scanned with ultrasound approximated the reference data set values. To be considered accurate, experimental sets should show not only trueness (closeness to the experimental data set) but also precision (agreement among repeated measurements). However, in this study, the accuracy of ultrasound was not assessed.

The results suggested the potential of this high-frequency intraoral ultrasound scanner for taking digital impressions of dental implants. A mean discrepancy of 57.40 ± 17.44 µm was found, values considered acceptable from the clinical point of view [12].

Ultrasound scanning is a sensitive technique, in which acoustic waves are transmitted through the object and are reflected back, providing data to the image reconstruction software [23,24]. Due to its non-ionizing nature, it might be used regularly to scan dental implants for different purposes. Previous studies have summarized the use of ultrasound in dentistry [25–31]. Although its clinical use is not yet a standard procedure, literature reports have cited the extra benefit, in addition to impression, of assessing and monitoring hard and soft tissues around dental implants [15,16,25,26]. To the best of the authors' knowledge, this is the first study using an ultrasonic technique for taking digital implant impressions.

The scanning of dental implants using ultrasound would be especially effective in cases of impression, including teeth prepared at subgingival level. An ultrasound-based technique is able to penetrate soft tissues and scan the subgingival margin of the preparation without being subject to the influence of oral fluids [20,21]. As the disadvantages of this technology, the following can be highlighted: (1) the need for a medium, such as water or gel, to enable ultrasound wave propagation, and (2) its susceptibility to noise and artifacts that would hamper 3D image reconstruction [22]. In addition, when compared with optical scanners, at present, the ultrasound technique requires more time to scan an object.

The main advantage of ultrasound-based scans is the wave penetration into soft tissues [14]. Marotti et al. (2019) showed that a 75 MHz ultrasound scanner was able to reproduce subgingival margins of the prepared tooth [20]. Scanning with a high-frequency ultrasound scanner can be beneficial when scanning dental implants together with prepared teeth since the main advantage of scanning with ultrasound is that it is capable of scanning the subgingival region of a prepared tooth.

Furthermore, its insensitivity to oral fluids makes the technique suitable when it is necessary to take dental implant impressions with an open flap. For digital implant impression taking, the gingival phenotype and reduced height of the scan body could possibly be limiting factors for the use of ultrasound scanners [11,21].

A frequency of 42 MHz was chosen to provide the resolution required for intraoral scanning to the detriment of the penetration depth [14]. The resolution of the transducer selected was to the order of 20 µm axial and 70 µm lateral, required for robust matching of the complex surface geometries within the oral cavity. By using a 42 MHz transducer, a maximal penetration depth of 2.14 mm was achieved [32]. Marotti et al. (2019) showed that a similar ultrasound scanner with a 75 MHz probe was able to scan gingiva with a thickness of up to 1 mm [20]. These parameters were considered sufficient for the clinical purposes of this study.

Previous studies evaluating the use of ultrasound in implant dentistry were based on B-mode images for recognizing anatomical structures [17,27]. Nonetheless, the aim of implant impression is to reproduce the spatial position of dental implants in relation to the adjacent structures, thus requiring a 3D image of surface structures [30]. By reconstructing B-mode images based on the spatial position of surface echo points, this requirement was achieved [23].

The major challenge of ultrasound technology is to develop a probe with sufficient accuracy and efficacy to scan intraoral tissues. The ultrasound scanner used in this study is a latest generation scanner developed specifically for this purpose. High lateral and axial resolution and accuracy are achieved by using a focused high-frequency single element transducer [33]. Furthermore, in order to increase the depth of field, a synthetic aperture focusing technique was used [34,35].

Whereas the intraoral scanner showed the lowest measurement error, the highest deviation from the reference dataset was shown in laboratory scans. This deviation may possibly be related to the application of powder prior to scanning. However, powder is not mandatory for all laboratory scanners. In this study, the powder was applied to facilitate the detection of the acrylic resin surface since the material can show high reflectivity [36]. Likewise, these findings should be carefully interpreted since they do not represent a clinical situation.

With regard to ultrasound, the main challenge is to maintain uniformity of the scan since the technique is sensitive to environmental variations, such as the variation on tissue surfaces [37]. Another limitation of this study was the small sample size. Although clinical features must be taken into consideration in future studies, ultrasound accuracy under different conditions was beyond the scope of this study.

In this regard, some factors must be considered when performing ultrasound scanning. First, during the scanning, movements must be suppressed. For this purpose, an individual tray was developed containing a fixation structure that had exactly the same dimensions as those of the ultrasound probe. Second, the high difference in impedance between air and tissue was avoided with the use of an acoustic coupling. This was possible with the application of an ultrasound gel on the scanned site. This step has to be accurately performed to avoid the formation of bubbles, which may hamper the scanning process [35].

The time required for ultrasound scanning was two minutes, which can be considered acceptable for scanning one single dental implant. However, these findings are still not appropriate for the scanning of multiple dental implants. As recommendations for further studies, the simulation of clinical conditions should be investigated.

5. Conclusions

The high-frequency ultrasound scanner showed a trueness value comparable with that of optical scanners for the scanning of a dental implant in the position of an upper central incisor. Ultrasound-based scans showed a mean discrepancy value lower than 60 µm, which was considered acceptable from the clinical point of view.

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

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