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How should I scan for measurement accuracy in full-arch scans?

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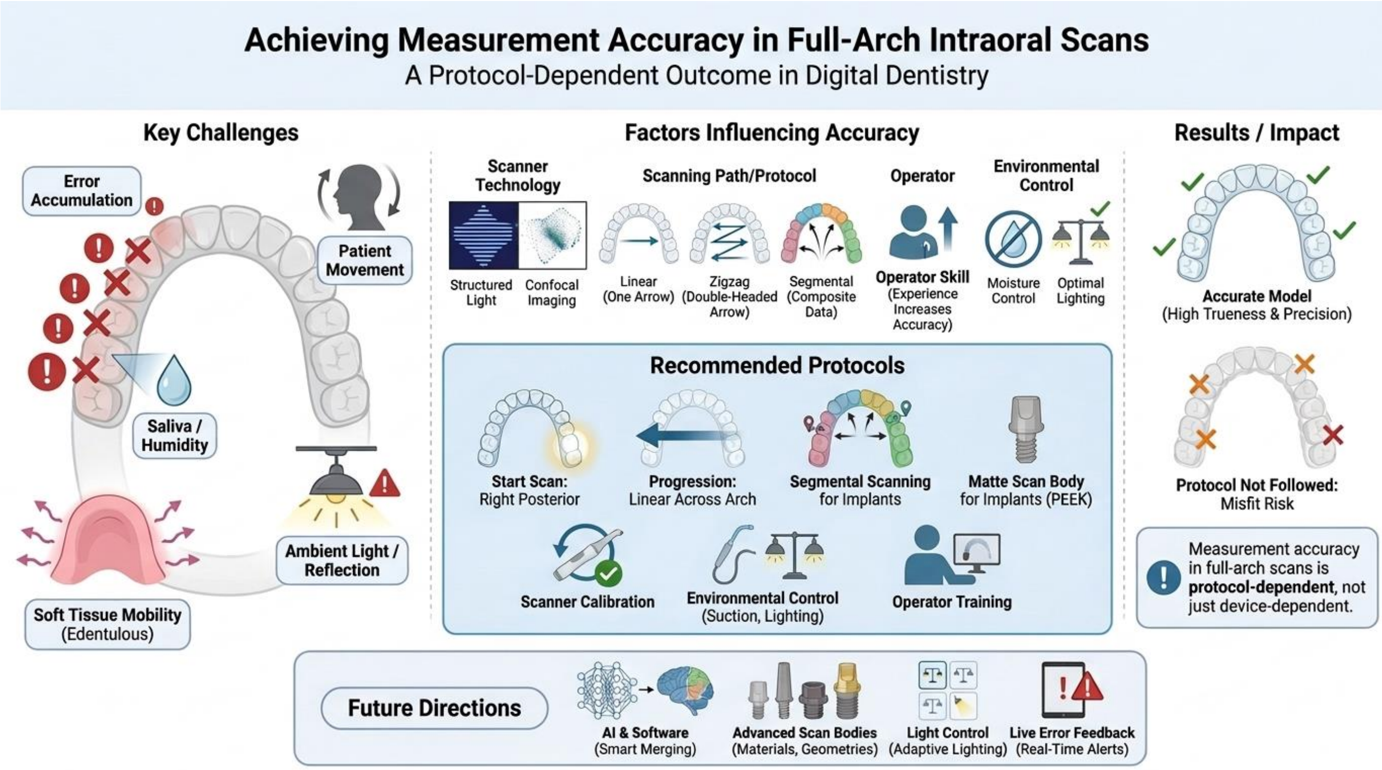
Abstract

The integration of intraoral scanners (IOSs) into routine clinical practice has transformed full-arch digital impression-making, offering improved patient comfort and the potential for high measurement accuracy. However, ensuring reliable trueness and precision across large arch spans remains challenging because of the cumulative errors that arise when extended areas are scanned, which can compromise the fit of prosthetic restorations, generate stress within implant-supported frameworks, and introduce clinically relevant errors in orthodontic planning. This review synthesizes the current evidence on the technical, biological, and operator-related factors that influence full-arch scanning accuracy and outlines clinically applicable strategies to minimize error. The principal challenges discussed include local error accumulation, patient movement, saliva and moisture, soft-tissue mobility in edentulous arches, and operator fatigue, all of which can lead to volumetric deformation of the digital model. Key determinants of accuracy are examined, including scanner technology, scanning path and starting-point selection, operator experience, oral humidity, ambient light, and implant scan-body characteristics. Recommended scanning patterns—linear, zigzag, and segmental approaches—are compared and discussed, together with region-specific strategies for the anterior and posterior segments. The evidence indicates that a disciplined protocol markedly improves trueness and precision: linear progression from the posterior toward the anterior region, segmental scanning in implant-supported cases, regular scanner calibration, a constant scanning speed and distance, effective moisture and ambient-light control, the use of matte scan bodies such as PEEK, and continuous operator training. Future research should prioritize intelligent auto-alignment algorithms, standardized implant scan-body geometries and materials, multicenter evaluation of environmental conditions, and artificial-intelligence-based real-time error detection to further enhance the reliability of digital impressions in clinical practice.

Keywords: Full-arch scanning, intraoral scanner, trueness and precision, segmental scanning, digital impression

Graphical abstract



1. Introduction

Technologies used in digital dentistry have gained significant momentum in recent years, especially the integration of intraoral scanners (IOSs) into clinical applications, which has started to offer significant advantages in terms of patient comfort and treatment accuracy by replacing traditional measurement methods (1). In particular, full-arch scans have a wide range of clinical applications, from fixed prosthesis planning to implant-supported restorations and orthodontic treatment processes. However, ensuring measurement accuracy in this field of application requires controlling the accumulation of errors that may occur during the scanning of large areas (1).

The accuracy of digital models in full-arch scans is a critical parameter for the success of treatment processes. Measurement accuracy consists of two basic components: trueness (matching the measurement with the actual model) and precision (repeatability) (2). Deficiencies in the trueness level can lead to incompatibility of prosthetic restorations, stress accumulations between implant-supported structures, and errors that cannot be ignored in orthodontic treatments (3).

On the other hand, in measurements where the precision value is low, incompatibilities occur between scans taken at different times; this situation reduces predictability in the treatment processes. Therefore, providing both trueness and precision values at optimum levels in full-arch scans is of great importance for the success of clinical results (2).

Full-arch measurements are used in different clinical areas, such as implant-supported prosthesis planning, edentulous jaw rehabilitation, and orthodontic treatment planning. However, small error accumulations that may occur during the scanning of large areas can turn into larger deformations over time, negatively affecting the clinical compatibility of restorations (4).

In this context, the selection of the right scanning techniques and the effective use of the scanner technologies used are of critical importance in order to achieve high accuracy in full-arch scans. Studies in the literature reveal that intraoral scanners can provide levels of accuracy close to or superior to conventional measurement methods when used systematically and in a disciplined manner (5).

2. Challenges encountered in scanning

Full-arch scans are one of the most technically sensitive applications among the digital measurement methods offered by IOSs. However, this process faces various challenges arising from both biological and technical factors. In this section, the main challenges encountered in full-arch scans and their effects on clinical results are discussed.

During full-arch scans, there is a risk that local measurement errors will accumulate over time and result in total volumetric deformations. These deformations, especially the measurement discrepancies that may occur between the posterior and anterior regions, can negatively affect the success of restorative treatments (1). In a systematic review conducted by Vitai et al., it was reported that the risk of deformation in full-arch scans is significantly higher than in short-segment scans (1).

Small movements of the patient, changes in tongue position, or involuntary reflexes during scanning can make it difficult to align digital images correctly. In addition, moisture and saliva accumulation in the mouth can prevent the scanner light from reflecting correctly from the surfaces, leading to data loss or image artifacts (2). Revilla-León et al. emphasize that failure to control saliva during scanning can cause serious deviations in measurement accuracy (2).

In edentulous cases, the flexible structure of the alveolar mucosa makes it difficult for scanners to determine fixed reference points, which can lead to deformations in the scan data and position shifts in digital models. Srivastava et al. revealed that soft tissue mobility is one of the most important factors in accuracy loss in scanning edentulous arches (4).

Another study by Gan et al. indicated that including the palatal region in the scanning process, especially in full maxillary scans, increases deformation rates; however, advanced alignment software can reduce these deviations (6).

During long-lasting full-arch scans, factors such as operator fatigue and distraction can negatively affect the ability to use the scanner at a constant speed and distance. This can lead to data loss on the scanned surfaces and a deterioration in the scanning accuracy (2). In a study conducted by Yuzbasioglu et al., it was reported that patient cooperation decreased in long-term scans and that prolonged scanning times negatively affected patient comfort (7). Güth et al. revealed that deformation rates increased in cases where mobile tissues could not be stabilized throughout the entire arch (8).

In light of these difficulties, the scanning protocols to be applied in full-arch scans and the scanner technologies to be used should be carefully selected.

3. Factors affecting accuracy

The accuracy of digital measurements obtained in full-arch scans is not limited to the scanner technology used; it depends on many factors, such as the applied clinical protocols, operator experience, and environmental factors.

3.1 The role of scanner technology

The working principles of IOSs vary according to the technological infrastructure used. Methods such as structured light, confocal imaging, and optical coherence tomography are the main technologies that determine how data are obtained and processed (6).

While structured light systems provide high-resolution surface details, confocal systems offer advantages especially in depth perception. However, in both methods, the risk of error accumulation increases as the scanning distance increases; this situation can negatively affect clinical accuracy, especially in full-arch scans. Revilla-León et al. state that structured light-based scanners provide more consistent results in posterior regions, while confocal systems are more successful in detail resolution in anterior regions (2).

3.2 Scanning path and starting point selection

To preserve the integrity of a digital model, determining the path and starting point to be followed during scanning is a critical step. A widely accepted method in the literature is to advance linearly from the posterior region to the anterior region (2).

This approach minimizes the accumulation of small errors that may occur throughout the scan and provides a more homogeneous data flow, especially in implant-supported restorations. However, protocols such as cross-lines or segmental advancement may provide advantages in terms of accuracy, especially in long-arch scans. Gan et al. showed that the segmental scanning method significantly reduced alignment deviations in full-arch measurements (6).

3.3 The effect of operator experience

The success of the scanning process depends largely on the operator's experience. Experienced users ensure that the data are processed homogeneously by holding the scanner at a constant speed and distance. Mai et al. reported that experienced users can use fixed-angle advancement techniques more effectively and reduce the risk of deformation (9).

On the other hand, more inconsistent scanning movements of new users can lead to both longer scanning times and increased data loss. In this context, Revilla-León et al. state that segmental scanning protocols are more applicable to new users and accelerate the learning process (2).

3.4 The effect of oral humidity and environmental conditions

The humidity level in the mouth is another factor that directly affects the accuracy of digital impressions. Excessive saliva can prevent the scanner light from reflecting correctly on the surfaces; this can cause artifacts on the digital model and data loss (2).

Therefore, especially in full-arch scans, it is necessary to keep the mouth as dry as possible before the procedure and to ensure saliva control during scanning. Alghazzawi detailed the effects of ambient light, lens cleaning, and patient positioning on scanning results and emphasized that humidity control, especially in posterior regions, plays a decisive role in scanning quality (10).

Revilla-León et al. state that the light sources used in the clinical environment can affect scanner performance and that high light intensity can cause reflection problems in optical sensors (2).

4. Recommended scanning methods

To ensure high accuracy in full-arch scans, the correct scanner selection alone is not sufficient; the scanning strategies to be applied must also be carefully determined. Studies in the literature reveal that scanning methods have a decisive effect on both measurement accuracy and the data processing process.

4.1 Scanning patterns: Linear, zigzag, and segmental methods

Linear, zigzag, and segmental methods are prominent among the scanning patterns used for full-arch scanning. These methods should be selected according to the anatomical structure of the area to be scanned, the cooperation of the patient, and the scanner technology to be used.

- **Linear scanning:**
  In this method, the scanner collects data from the occlusal surfaces of the teeth to the vestibular and lingual surfaces by moving along a fixed line. Especially in patients with full dentition, linear scanning provides advantages in terms of minimizing error accumulation and obtaining more homogeneous data (6, 7). However, this method should be applied with caution to long-arch structures, as it can sometimes increase the risk of deformation.
- **Zigzag scanning:**
  The zigzag scanning method involves collecting data with continuous back-and-forth passes over the tooth surfaces. This method allows for a better perception of surface details in cases with distinct occlusal morphology. However, due to data redundancy, the processing of scan data can become more complex, which can increase the load on software algorithms (2).
- **Segmental scanning:**
  In long-arch structures, scanning the right, left, and front regions separately instead of a single scan and then combining them is called the segmental scanning method. In this method, since each segment is scanned independently, the accumulation of alignment errors is prevented, and the risk of total deformation is reduced (9). Gan et al. stated that segmental scanning allows for more consistent digital models, especially in full-arch implant cases (6).

4.2 Posterior and anterior region strategies in clinical practice

The choice of path to be followed during scanning is a factor that directly affects the accuracy of the digital model to be obtained. Since the posterior and anterior regions differ in terms of their anatomical structures and accessibility, the scanning strategies to be applied in these regions should also be different.

- **Posterior region:** In the posterior regions, it is important for the scanner to advance at a constant speed and angle due to the narrow field of view and high saliva accumulation. Maintaining this steady advancement ensures homogeneous collection of data and reduces the risk of deformation. In addition, it is recommended to work with minimal angular changes so that the scanner head can clearly detect each tooth surface (9).
- **Anterior region:** Since the anterior regions have large surfaces and distinct morphological contours, the scanner may need to make wider sweeping movements. In this region, it is important for the scanner to advance at a regular speed across the surface, both to maintain data integrity and to optimize scanning time.

Revilla-León et al. state that sweeping movements applied in the anterior region provide more homogeneous data flow and that narrow-angle transitions made in the posterior region reduce the risk of deformation (2).

Mai et al. reported that scans performed in the anterior region generally take less time and that scanning small segments separately in the posterior region reduces data loss (9).

4.3 Implant-supported scanning specifications

Full-arch scans in implant-supported restorations are one of the applications where error accumulation is most frequently observed. Therefore, clear scanning of the scan body surfaces and complete processing of the obtained data are critical stages in implant-supported restorations.

- **Scanning of scan body surfaces:**
  Ma et al. stated that incomplete scanning of the scan body surfaces in implant-supported restorations can lead to rotational deviations and alignment errors (3). The clear capture of all contours of the scan body surface during scanning increases the accuracy of the obtained digital model.

- **Surface material and reflection problems:** Mangano et al. emphasize that glossy surfaces may cause data loss during scanning due to light reflection; therefore, preferring matte-surface scan bodies such as PEEK will provide more accurate results (5).
- **Scanning order and regional approach:** Srivastava et al. reported that starting from the posterior regions and providing a linear progression towards the anterior region in implant scans can reduce alignment deviations, especially in multi-unit restorations (4).

In a systematic review by Carneiro Pereira et al., it is stated that scan body sequences should be optimized in order to increase accuracy in implant-supported rehabilitations. In this study, it was reported that the data obtained with segmental scanning in the posterior regions were more stable, and data loss decreased in long-arch structures (11).

5. Scan protocols recommended in current literature

Advances in digital scanning technologies have paved the way for the development of protocols that aim to increase the measurement accuracy. These protocols in the literature have been shaped to include elements such as starting point selection, progression strategy, and segmental scanning techniques. In this section, scanning protocols that can be applied in clinical practice will be evaluated in light of current studies.

5.1 Starting point and advancement strategies

The starting point and advancement strategy of full-arch scans are among the factors that directly affect the scanning accuracy. One of the most recommended methods in the literature is to start from the right posterior region and advance towards the left posterior region (11, 12). This method minimizes alignment deviations and preserves data integrity, especially in implant-supported cases.

In a study by Medina-Sotomayor et al., it was stated that the scanning strategy applied has a significant effect on the accuracy of complete-arch impressions, and that the magnitude of this effect differs between scanner systems (13). Accordingly, the scanning sequence should be selected together with the scanner to be used rather than applied as a single universal protocol.

Robert et al. showed that optimizing the scanning order not only increased the measurement accuracy but also significantly shortened the processing time (14). It has been reported that alignment deviations are smaller, and data loss is minimized in models obtained with the segmental scanning method, especially in long-arch structures.

5.2 Scanner calibration and environmental conditions

To maintain scanning accuracy, not only the selection of the appropriate starting point but also the calibration of the scanner and control of environmental conditions are of great importance.

Revilla-León et al. state that the performance of optical scanners used in the clinical environment is directly affected by environmental factors such as ambient light and saliva control (2). In this study, it was stated that excessive light intensity can cause reflection problems in optical sensors, which can increase data loss, especially in the posterior regions.

Srivastava et al. showed that ensuring moisture control in the mouth before scanning reduces the risk of deformation, especially in edentulous cases (4). Moisture control increases the data collection sensitivity of optical sensors in particular and maintains the stability of digital models.

In an in vitro study conducted by Kanmaz et al., a scanner left uncalibrated for 324 days showed no statistically significant deterioration in either trueness or precision values (15). The authors nonetheless recommend adherence to routine calibration intervals until further evidence is available, and calibration status should be documented as part of the clinical protocol.

5.3 Pre-scan preparation and patient positioning

Appropriate intraoral preparations before the scanning process are among the factors that directly affect the quality of the digital impressions obtained. In full-arch scans, correct positioning of the patient and controlling intraoral moisture are important.

In a study by Rapone et al., the performance of three different IOSs in the presence of saliva was evaluated, and it was reported that wet environmental conditions made it difficult to perceive marginal details, especially in the subgingival regions (16). In this study, drying the intraoral surfaces before scanning significantly increased the accuracy of digital measurements.

Ochoa-López et al. evaluated the effects of environmental light levels and intraoral mobility on scanner performance and reported that high light intensity causes reflection problems during scanning, resulting in data loss (17). Therefore, it is recommended to optimize the light level in the clinical environment before scanning and to control patient mobility during scanning.

5.4 Clinical tips to increase measurement accuracy

As the clinical use of digital IOSs increases, the need to optimize the accuracy and reproducibility of digital measurements obtained in full-arch scans becomes increasingly important. In light of the findings obtained from the literature, some basic recommendations that can be applied in clinical practice are as follows:

- **Scanning protocol:** A linear progression should be provided starting from the posterior region and moving anteriorly; in implant-supported cases, a segmental scanning protocol should be used (11, 13, 14).
- **Scanner calibration:** Scanners should be regularly calibrated in accordance with the manufacturer's protocols prior to clinical use. The lack of calibration is one of the main factors that negatively affect measurement accuracy (15, 17).
- **Scanning speed and distance:** The scanner should be advanced at a constant speed and scanner-tissue distance; sudden changes in direction should be avoided (2, 9).
- **Use of scan body:** In implant-supported applications, using scan bodies with matte surfaces and minimizing light reflection will increase scanning accuracy (5).
- **Control of environmental conditions:** Oral moisture should be controlled, excess saliva should be removed, and ambient light should be balanced before the scanning process (16, 17).
- **Operator training:** Operators should have sufficient theoretical knowledge and practical experience to implement the segmental scanning protocols. Continuous training plays a critical role in minimizing operator-related errors (4, 9).

The disciplined application of these recommendations in clinical practice will increase the accuracy of digital impressions and contribute to the success of restorative treatment processes.

6. Future research and development areas

Digital dentistry applications have undergone a significant transformation process with the integration of IOSs and CAD/CAM systems. However, the current literature reveals that digital scanning technologies have some limitations and areas for improvement, and that a number of questions remain unanswered. Four areas emerge as priorities for future studies: algorithm-based alignment of scan data, the geometry and material of scan bodies, the control of ambient conditions, and real-time error detection. Each of these is examined in turn below; progress in these areas can further increase the accuracy of digital impression systems and their effectiveness in clinical applications.

6.1 Software-based developments: Smart algorithms and data integration

Software-based developments play a critical role in processing scan data more precisely and increasing the stability of the digital models. In particular, smart algorithms that will automatically align segmental scan data can minimize data loss and alignment deviations.

In a systematic review by Carneiro Pereira et al., it was emphasized that the algorithms used to align scan data should be made more intelligent and adaptive, especially in long-arch structures (11). In the same study, it was stated that making the scan body geometries used in implant-supported cases compatible with software-based alignment algorithms could increase digital model accuracy.

Ma et al. stated that software that provides instant feedback to the operator during scanning can prevent data loss and alignment errors (3). Such a feedback system stands out as a feature that can accelerate the learning process, especially for new users.

6.2 Implant scanning protocols: Effect of material and geometry

The effects of scan body materials and geometries used in implant-supported restorations on scanning accuracy are not yet fully understood. Studies comparing the effects of different materials and surface structures on the scanning performance are required (18).

Mangano et al. reported that PEEK material increases scanning accuracy by reducing light reflection (5). However, the performance of different materials, such as titanium or zirconia, during scanning has not been studied in detail in clinical settings.

Srivastava et al. stated that selecting a shorter and wider scan body geometry, especially in posterior implant cases, reduces data loss during scanning (4). However, this finding should be confirmed in larger clinical studies.

In this context, it is suggested that future research should focus on the following questions:

- How can the compatibility of the scan body material with optical sensors be optimized?
- What is the effect of different scan body geometries on rotational deviations?
- In multi-unit implant scans, which provides more consistent results: segmental scanning or a single scan?

6.3 Effect of ambient conditions on digital impression accuracy

Ambient conditions during intraoral scanning are among the factors that directly affect the optical sensor performance of the scanners. Factors such as ambient light, intraoral temperature, intraoral humidity, and patient mobility can increase the error rate, especially in full-arch scans.

Revilla-León et al. emphasize that the performance of optical scanners is greatly affected by ambient light and humidity (2). However, standard protocols for controlling these factors in clinical environments have not yet been established.

Ochoa-López et al. reported that optimizing ambient light during scanning reduces reflection problems, especially in posterior regions (17). However, this study did not address in detail the effect of different light sources (e.g., LED, halogen) on the scanner performance.

In this context, it is recommended that future research, preferably with multi-center designs, focus on the following issues:

- What are the recommended light sources for optimizing ambient light in clinical environments?
- How can the effect of humidity control on the scanning accuracy be minimized?
- How can the effect of patient mobility on data loss during scanning be measured?
- What effect do intraoral temperature fluctuations have on optical sensor performance during scanning?

6.4 Real-time error analysis and artificial intelligence support

Instant detection of error accumulations that may occur during scanning is of great importance in terms of preserving the accuracy of the digital model, especially in long-arch structures. In this context, supporting scanner software with artificial intelligence-based systems that can perform error analysis and provide instant feedback to the operator can be an effective step in increasing clinical success.

In a multicenter study by Giuliodori et al., it was reported that experienced operators applying a segmental scanning protocol had a positive effect on digital accuracy when they determined the starting point and progression strategy in advance (19). In the same study, it was stated that instantaneous monitoring of data loss during scanning and providing feedback to the operator that the faulty area should be rescanned increased the accuracy of the obtained digital models.

Mai et al. showed that complete-arch scan accuracy depends on the scan strategy and the segmental scan-and-merge method applied rather than being a fixed property of the device; real-time feedback on scan quality is therefore a logical extension of this finding, especially in implant-supported cases (9). Such an error analysis system can be considered as a tool that can accelerate the learning process, especially for new users.

7. Discussion

The rapid increase in the use of digital IOSs has brought the issue of measurement accuracy in full-arch scans to critical importance in terms of both clinical applications and scientific research. The current literature evaluated within the scope of this study reveals that the factors affecting scanning accuracy are multidimensional and that these factors interact with each other.

The accuracy of digital measurements obtained in full-arch scans may vary greatly depending on the scanning strategy applied and the technological infrastructure of the device used. In the literature, the effects of factors such as the selection of the region to be scanned, scanner speed, and scanning protocol (e.g., linear or segmental) on measurement accuracy have been frequently emphasized (2, 4, 9).

It has been reported that the segmental scanning method reduces the risk of deformation, especially in long-arch structures, and the obtained models contain more stable digital data (13, 14). However, the effectiveness of the segmental protocol is directly dependent on operator experience and the alignment precision of the scanner algorithms (9, 20).

The success of the scanning process depends largely on the experience of the operator and the correct application of the protocol used. It is stated in the literature that experienced operators use fixed-angle advancement techniques more effectively and thus achieve more successful results in both trueness and precision values (9).

On the other hand, it is stated that new users may cause data loss with inconsistent movements, and this situation becomes especially evident in full-arch scans. In this context, the continuity of operator training and the applicability of segmental scanning protocols in practice are of great importance in terms of clinical accuracy (4, 9).

Revilla-León et al. stated that acquiring basic technical skills such as keeping the scanner speed constant, maintaining the scanner distance, and making the correct starting point selection by operators will directly increase scanning accuracy (2).

In implant-supported restorations, the accumulation of errors that may occur in full-arch scans is one of the most important factors that can lead to clinical compatibility problems. Therefore, complete and accurate scanning of implant surfaces during scanning directly affects the accuracy of the obtained digital model.

Ma et al. emphasized that incomplete scanning of the scan body surfaces can lead to rotational deviations and alignment errors (3). Therefore, it is recommended that scan body materials used in implant-supported cases should be selected from matte surfaces that do not cause optical reflection, and that all surfaces should be scanned completely.

Mangano et al. reported that PEEK material provides more stable data by reducing light reflection (5). Srivastava et al. stated that the segmental scanning protocol contributes to obtaining more consistent models, especially in posterior implant cases (4).

The quality of the data obtained during digital scanning is not limited only to the scanner technology and the applied protocol; it is also closely related to the conditions of the clinical environment. In the literature, it is stated that controlling intraoral moisture and optimizing ambient light are among the factors that increase scanning accuracy (16, 17).

In the study by Rapone et al., it was reported that excessive saliva accumulation during scanning caused data loss, especially in subgingival regions, and this could cause deformation on the digital model (16). In the study, it was emphasized that drying the mouth and removing excess saliva before scanning increased the scanning accuracy.

Kanmaz et al. reported that when an optical scanner was left uncalibrated for 324 days, no statistically significant deterioration was observed in either trueness or precision values (15). This finding suggests that the influence of calibration intervals on digital impression accuracy is less pronounced than commonly assumed and warrants further investigation.

For digital impression technologies to be used effectively and correctly, not only the selection of the scanner technology but also the implementation of the correct scanning protocol, operator training, and control of clinical environment conditions should be carefully planned. Addressing these factors with a holistic approach is critical in terms of increasing the accuracy of digital impressions and ensuring sustainable success in restorative treatment processes.

The literature findings evaluated in this study show that digital impression accuracy is not limited to scanner hardware alone; they also reveal that it is affected by many factors such as scanning protocol, operator experience, scan body material, environmental conditions, and software algorithms. It should be noted, however, that a substantial part of this evidence derives from in vitro investigations conducted under controlled conditions, in which intraoral moisture, patient movement, and restricted access are not fully reproduced. The protocol recommendations summarized here should therefore be regarded as clinically plausible rather than definitively validated, and they require confirmation in prospective in vivo studies.

8. Conclusions

Measurement accuracy in full-arch scanning is determined less by the scanner itself than by the interaction of scanning strategy, operator skill, scan body selection, and clinical environment. The evidence reviewed in this article supports a linear progression from the posterior towards the anterior region, a segmental protocol in implant-supported cases, regular calibration of the scanner, matte-surface scan bodies, and deliberate control of intraoral moisture and ambient light. Where these conditions are met, intraoral scanners provide trueness and precision values comparable to conventional impression techniques; where they are not, local errors accumulate across the arch and appear clinically as misfitting restorations. Measurement accuracy in full-arch scans should therefore be regarded as a protocol-dependent outcome rather than a fixed property of the device.

In future research, especially the software optimization of segmental scanning protocols, the examination of the performance of matte-surface scan bodies in implant-supported restorations, and the development of artificial intelligence-based systems that will provide real-time feedback to the operator during scanning have significant potential to increase clinical success.

As a result, improvements in digital scanning technologies will not only increase measurement accuracy; they will also contribute to the completion of clinical processes in a shorter time and with fewer errors. Multidisciplinary studies focusing on these development areas will play an important role in determining the future roadmap of digital dentistry.

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Declaration of Generative AI and AI-Assisted Technologies: During the preparation of this work, FigureLabs was used to create the graphical abstract, and the AI figure-generation feature in BioRender was used for subsequent text edits to the figure. The author(s) then reviewed, edited, and verified all visual and scientific content for accuracy and take(s) full responsibility for the final published material.

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