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Comparison of scanning accuracy of different digital intraoral scanners

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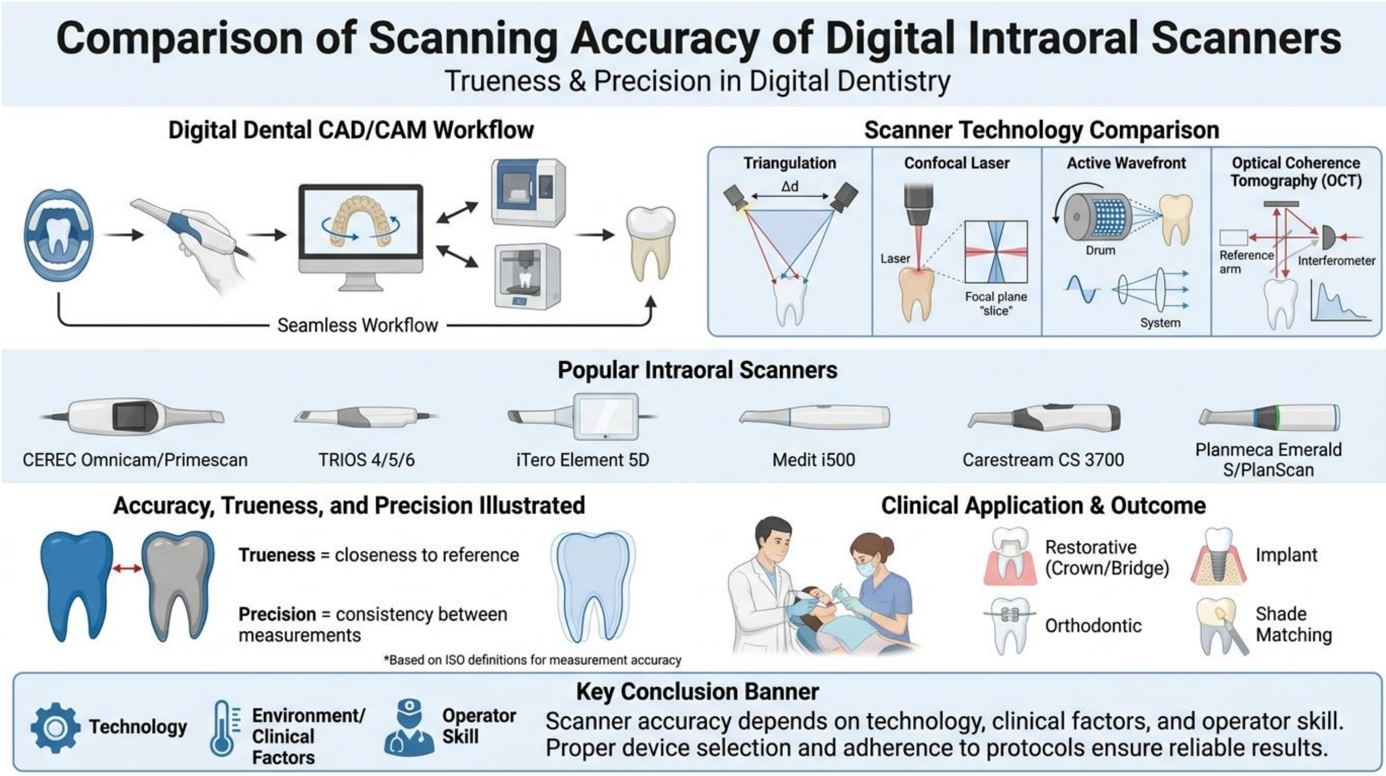
Abstract

Digital intraoral scanners (IOSs) have gained significant importance in modern dentistry by offering accurate, efficient, and patient-friendly alternatives to conventional impression techniques. This review aims to evaluate and compare the image quality and accuracy provided by various intraoral scanners, focusing on the current literature. Factors influencing image quality, such as scanning technology (confocal microscopy, triangulation, active wavefront sampling), operator experience, and scanning strategy, are also discussed. The evaluation includes commonly used IOS devices, including iTero, Trios, Medit i700, and CEREC Primescan, analyzing their performance in clinical and laboratory conditions. The literature suggests that while each scanner has strengths and limitations, all of them provide clinically acceptable results for prosthodontic and orthodontic applications. Furthermore, advancements in software and hardware are continuously enhancing image resolution, data acquisition speed, and ease of use. However, despite the progress, discrepancies in trueness and precision still exist depending on the scanning environment, scan area size, and material reflectivity. This review concludes that selecting an appropriate IOS should be based on clinical needs, operator preferences, and the specific task at hand. Continuous technological development and standardized evaluation methods are essential to further improve IOS reliability and integration into routine clinical practice.

Keywords: Accuracy, intraoral scanners, digital scanning, three-dimensional imaging, digital dentistry

Graphical abstract



1. Introduction

Today, with the development of computer-aided manufacturing and design (CAD/CAM), the term digital workflow has become prominent in dentistry (1). CAD/CAM systems offer patients better quality, more comfortable, and shorter treatment options than conventional methods. CAD/CAM systems consist of three functional units: first, the collection and recording of data; second, the computer-aided preparation of the restoration design; and finally, the fabrication of the restoration (2-4). Digital scanners play a role in collecting and recording the data.

With digital scanners, the risk of nausea and vomiting, and discomfort with the taste and odor of the impression material can be avoided. However, the presence of saliva and blood in the mouth can negatively affect the scanner's ability to obtain a precise image, and the cost of the devices and the need for experience are also disadvantages (5).

Image registration with digital scanners is achieved using two techniques. In the indirect technique, measurements are taken using traditional methods, and a model is obtained. A virtual model is then obtained by scanning this model with a laboratory scanner, and the design is made on this virtual model. In the direct technique, an impression is obtained using an intraoral scanner without traditional impression materials and transferred to a computer (6).

Digital scanners are classified into intraoral and extraoral types. Extraoral scanners are divided into model and desktop scanners. Milling machines or three-dimensional printers then produce the scanned and designed restorations.

With the recent development of digital systems, many companies have introduced digital scanners to the market, and these systems have pioneered research. The main aim of the scanners is to record the most accurate measurements, and the accuracy of the measurement varies from scanner to scanner. Before examining these differences, it would be useful to first examine how scanners work and the current scanners on the market.

Scanning technologies:

Different scanning technologies are used in intraoral scanners.

1. **Triangular scanning method:** This system uses three reference points to allow the scanner head to scan without touching the object. The camera, object, and light source form a triangular structure and are often used in conjunction with structured light technology. The systems are divided into passive and active triangulation techniques according to the light source.
    - **Passive triangulation:** Light from the object is detected by two cameras and

translated into an image. Stereovision algorithms are used and provide high accuracy but are only effective in high-contrast areas.

- **Active triangulation:** A laser beam is sent to the object, and its reflection is detected to obtain depth information. LED light can also be used instead of a laser. The camera measures the depth of the surface by determining the position of the laser spot. Since the laser is moving, the camera and the light source form a triangular structure. These techniques are preferred in different applications to improve scanning accuracy (7).

2. **Confocal laser scanning method:** Patented in 1961 by Marvin Minsky, the confocal technique is used to create depth contrast in high-resolution images. The system records a region-by-region image by shining fluorescent light from a light source onto the object and combining it on a computer. In principle, the lens moves to determine the x- and y-axes of the rays, while the fluorescent light reflected from the object generates the z-axis information. A special filter ensures that only the light from the object is detected, preventing unwanted reflections. The collected visual data is converted into electrical signals and transferred to a computer. This technique is used for high-precision depth analysis (7, 8).

3. **Active Wavefront Method (AWF):** The term wavefront is defined as the set of points with the same phase of the wave formed by the time-dependent propagation of a field of light. This refers to the wavefront formed by a light wave emitted from a source. In active wavefront technology, the emitted wave passes through one or two holes rotating in a moving cylinder. The images formed in this process are projected onto an image plane and processed using algorithms. The rotating cylinder structure helps reduce blurring in the image and provides a clearer visualization (8).

4. **Optical coherence tomography method:** In the interferometric imaging technique, images are created using light waves traveling in the same phase. The emitted light phases interfere with each other, and an algorithm is created based on the light phases reflected from the object. The interferometer in Optical Coherence Tomography (OCT) scanners separates the broadband light source into reference and sample fields. The sample field is focused deep into the tissue surface using scanning optics and an objective lens. The resulting image is recorded by interacting with the photo-detector surface. These systems consist of fiber-optic cables and optical components. The optical path includes a beam splitter (optical coupler), reflector, light source, optical delay line (ODL), and receiver. After exiting the source, the beam is directed to the coupler and then to the ODL and reflector. The image then travels back to the coupler and receiver. This beam reaching the receiver is called the reference beam. The spatial and temporal differences between the reference and sample beams merging in the optical coupler are calculated, and an image algorithm is generated on a computer (7).

Among these techniques, triangulation and confocal microscopy are the most widely used techniques to date.

Popular intraoral scanners currently used:

1. **CEREC® (Dentsply Sirona, Bensheim, Germany):** One of the first brands of scanners used in dentistry (9). Omnicam and Primescan are the most popular scanners. Primescan is the newest scanner. Chairside milling machines are available for this type of system (10).

   1.1. **Omnicam:** This scanner performs very fast color scanning, and continuous photographic images are converted into a three-dimensional model (10). The scanner tip facilitates scanning in posterior areas. It is used for fixed prosthetic treatments (inlays, onlays, crown-bridge restorations, etc.), bars, and orthodontic treatments (11).

   1.2. **Primescan AC®:** This scanner is a high-technology and fast device. It has a wide field of view and can capture large amounts of data, even when the device is held stationary. However, it supports limited applications, such as smile design, and has limitations on export. Two different versions of the software are available: Cerec Primescan AC and Primescan AC with connect software (10).

2. **Trios® (3Shape A/S, Copenhagen, Denmark):** Trios 3 and Trios 4 are the most commonly used scanners (11). Their most important features are their close color matching to real teeth and their success in recording margins.

   2.1. **Trios 3®:** Launched in 2015, it is widely used today and is available with a pen holder or pistol grip. In 2017, wireless scanners were introduced. It does not have a milling machine, so it can be exported in a universal format. It can be used for fixed prosthetic treatments (inlays, onlays, crown-bridge restorations, etc.), bars, implant modules, and orthodontic treatments (11).

2.2. **Trios 4®:** A fourth-generation scanner developed from Trios 3. It has a longer battery life than its predecessor and can scan the entire arch in 45 s. The color tone is generated automatically during scanning, and this information is maintained throughout the scan. It uses infrared light through its smart transillumination feature. This can help in the detection of invisible approximal caries. However, because this feature has not been approved by the FDA, it has no clinical use (12, 13).

2.3. **Trios 5®:** This is the smallest and lightest scanner among the Trios models. It has an autoclavable scanner tip with a thin sheath to reduce cross-infection. The scanner does not require calibration; however, unlike Trios 4, it cannot perform color analysis (14).

2.4. **Trios 6®:** This is the newest wireless model in the Trios series. Unlike the transillumination feature of Trios 4, it uses advanced hyperspectral imaging combined with artificial intelligence-assisted diagnostic software, extending detection beyond approximal caries to plaque, tooth wear, and gingival recession while providing accurate digital impressions. Like Trios 5, it is calibration-free and lightweight, and it is suitable for restorative, implant, and orthodontic workflows (15).

3. **iTero® (Align Technology Inc., Tempe, AZ, USA):** Introduced in 2007 and based on the principle of parallel confocal operation, the system has a scanner that emits light from a small area (16, 17). It generates digital data with 100,000 red light beams in one-third of a second using an intraoral appliance. Reflective powders, such as titanium dioxide, are not required for imaging. The system guides the physician with a voice command during scanning, and if necessary, the scanner can be removed from the mouth during scanning, and the scan can be resumed after drying the relevant area (18). The models include Element 1®, Element 2®, Element Flex®, and Element 5D®. All models have fast scanning, autocalibration, accelerated imaging, and network systems (10). Element 5D® is the latest model launched. It has near-infrared imaging (NIRI) technology. Thus, it can detect caries in real time during scanning.

4. **E4D (D4D Technologies LLC, Richardson, TX, USA):** This system was launched in 2008. It consists of a monitor, computer, laser scanner, and milling unit. It works with the optical coherence tomography scanning method. No special powder is required during scanning (19). With the E4D Dentist system, the preparation limits can be determined using automatic detection (20). It offers the possibility to examine the preparation from various angles via a touch screen. It works partly with CEREC technology, but Planmeca later released these systems as PlanScan (21).

5. **CS 3500®, CS 3600®, and CS 3700® (Carestream Dental LLC, Atlanta, GA, USA):** These scanners are capable of scanning with photographs and videos (7).

5.1. **CS 3500® and CS 3600®:** CS 3500® performs photo-based scanning, while CS 3600® performs video-based scanning (21). No reflective powder is required. They have a color scanning capability and can automatically determine the tooth color during scanning. Surface registration with fringe imaging and triangulation is required (22).

5.2. **CS 3700®:** This is the latest model and scans faster than the others. According to the manufacturer, it completes the entire arch scan in 30 s, and like the other models, it can automatically assign color and optically determine the tooth color (22).

6. **Lava™ C.O.S. (3M ESPE, St. Paul, MN, USA):** This system has its own milling unit. Titanium oxide sprays are used during the scanning process. After a full-arch scan, the jaws can be digitally brought into occlusion. During the measurement, marginal zone scanning is successful and accurate up to 120 µm (10).

7. **Dental Wings® (Dental Wings Inc., Montreal, QC, Canada):** This system can also be used to create partial dentures and surgical guides. Dwio and Virtuo Vivo models are available (11).

7.1. **Dwio®:** This scanner uses multiple LED lights and video recording. Initially, dust was used during scanning, but this feature was later improved. The most important feature is that it is light and small. The scanner is fast but does not have automatic color detection (11).

7.2. **Virtuo Vivo™:** This scanner is lightweight and ergonomic. There is no need to use powders or sprays during scanning. It has a realistic color scanning feature. It guides the physician during scanning using hand gestures and voice command features (11).

8. **MIA3d™ (Densys3D Ltd., Migdal Ha'Emek, Israel):** According to the manufacturer, this system is among the lightest and most easily operated scanners currently available. It is used in orthodontic and restorative treatments. Two-dimensional images are combined with a triangulation technique to form a three-dimensional image. Powder and spray are used during the scanning process (7).

9. **Emerald® (Planmeca Oy, Helsinki, Finland):** Emerald, Emerald S, and PlanScan models are

available. They have milling units, and their heads can enter the autoclave (23).

9.1. **Emerald® and Emerald S®:** These scanners work with projected pattern triangulation (Projected Pattern Triangulation™). No special powders are required during the scanning process. The latest model is Emerald S. Their scanner heads are lightweight and ergonomic. They provide real-time color imaging (23).

9.2. **PlanScan®:** A confocal microscopy scanning method is used. There are four different scan heads, each used for a specific region. It can be used to guide model preparation in synchronization with CBCT (11, 24).

10. **Zfx™ IntraScan (Zfx GmbH, Dachau, Germany):** This system captures 18 images per second. There is no need to use powder or spray during the scanning process. It works with the confocal measurement principle (25).
11. **Medit i500® (Medit Corp., Seoul, South Korea):** This scanner works with active triangulation technology. It offers color video-based scanning. There is no need for reflective powder or spray during the scanning process. It scans with three different laser beams. The light emitted from a projector is imaged by two stereo-vision oral scanners. Optical lens technology allows for a more compact head (26-28).
12. **Medit i700® (Medit Corp., Seoul, South Korea):** Introduced as the successor of the i500, this scanner also works with active triangulation and provides powder-free, full-color video-based scanning. Compared with its predecessor, it offers a higher frame rate, a wider capture area, and approximately twice the scanning speed, together with a lighter and more compact handpiece. In vitro full-arch studies have reported that the i700 achieves trueness and precision values comparable to, or better than, those of other contemporary scanners, with trueness values as low as 21-24 μm and a mean full-arch deviation of approximately 114 μm; its performance has also been shown to be relatively robust across different scanning strategies and operators (29-31).

Accuracy of intraoral scanners

An accurate dental impression is necessary for producing a good restoration. This refers to the concept of "accuracy," which is the main characteristic that a dental scanner should have. Therefore, the aim of treatment should be a perfect digital copy of the area to be restored. Not only the restoration area but also the adjacent and antagonistic areas, as well as the interocclusal bite relationship, should be scanned (32). According to ISO 5725, accuracy is based on two concepts (33).

1. Trueness describes how close a measurement is to the actual dimensions or reference value (33).
2. Precision describes how close measurements made with the same instrument are to each other (33).

The higher the precision, the more reliable the measurement; the higher the accuracy, the closer the measurement is to the actual dimensions of the object, as defined by ISO 5725 (33). In light of these terms, accuracy is the difference between the actual value and the value indicated by the model in the measurement of a physical property. According to the standard, the proximity of reality and precision determines the quality of accuracy.

2. Clinical and research consequences

In clinical use with new technologies, the literature shows that scanners are satisfactory for clinicians. Representative studies from the literature are summarized below.

Patzelt et al. evaluated the accuracy of full-arch scans using four different intraoral scanners (iTero, CEREC AC Bluecam, Lava C.O.S., and Zfx IntraScan); scan results were imported into 3D evaluation software and compared. A reference model with 14 prepared abutments was digitized with an industrial reference scanner for comparison. Mean trueness values ranged from 38 to 332.9 μm and mean precision values from 37.9 to 99.1 μm. The highest accuracy was achieved with the Lava C.O.S. device, while the lowest accuracy was observed with the CEREC AC Bluecam. Significant differences were found between the CEREC AC Bluecam and other scanners in terms of average accuracy and precision, and differences were also found between some scanning procedures for each scanner. The authors concluded that, except for one system, all tested scanners showed a comparable level of accuracy for full-arch scans of prepared teeth (34).

In another in vitro study, Akkal et al. compared the three-dimensional (3D) accuracy of three different digital intraoral scanners (Primescan [PS], Trios 4 [TR], and Carestream 3600 [CS]) in full-jaw implant measurements using a model with implants placed at different angles and parallels in a completely edentulous jaw. Ten repetitions were performed for each group. The accuracy of the measurements was evaluated by comparison with a reference model. The results revealed that the Primescan group had the highest accuracy of 38 μm, while the Trios 4 and Carestream 3600 groups showed lower accuracy values of 104 μm and 171 μm, respectively. Notably, the Carestream 3600 scanner was found to have the highest deviation (35).

Casucci et al. evaluated the accuracy and sensitivity of IOS devices in scanning subgingival vertical preparations. Four different intraoral scanners were used in the study: Trios 3 (3Shape A/S, Copenhagen, Denmark), Medit i700 (Medit Corp., Seoul, South Korea), Vivascan (Ivoclar Vivadent AG, Schaan, Liechtenstein), and an Experimental IOS (GC Corporation, Tokyo, Japan). Subgingival vertical preparations of teeth 16 and 21 were prepared on a phantom model in the maxilla. The model was scanned using a laboratory scanner (Aadva Lab Scanner; GC, Tokyo, Japan), and a reference model was obtained. The model was scanned 10 times with each IOS, and a total of 40 digital molds were obtained. The digital molds were transferred to Geomagic Control X software (3D Systems, Rock Hill, SC, USA) and compared with the reference model to evaluate accuracy and precision. In terms of accuracy, Vivascan showed the lowest value for tooth number 16, while Vivascan and Experimental gave the best results for tooth number 21. In terms of precision, the Vivascan, Experimental IOS, and Trios 3 devices showed higher precision values. These findings emphasize the importance of device selection for the digital monitoring of subgingival margins. It is also concluded that due to the difficulties of scanning deep subgingival preparations, margin positioning and scanning techniques should be carefully planned in clinical practice (36).

Ebeid et al. evaluated the performance of various intraoral scanners in accurately and consistently determining tooth color. In digital dentistry, it is important to create prosthetic restorations that match the natural tooth color of patients. Three different scanners were used in the study: 3Shape Trios, Cerec Omnicam, and Cerec Primescan. Shade determination was performed on different dental shades using each scanner. The color tones determined by the scanners were compared with a reference system (VITA Easyshade V spectrophotometer; VITA Zahnfabrik, Bad Säckingen, Germany). Multiple scans were performed using the same scanner to verify the consistency of the results. In terms of accuracy, this study found significant differences in color identification accuracy between different IOS models. According to the findings of the study, there were significant differences in the accuracy of tooth color identification between the devices ($p < 0.001$). The instruments also showed lower repeatability than expected. These results suggest that instrumental shade determination should be used with caution and supported by experienced visual assessment (37).

In another study, Leven et al. examined the fitting accuracy of digital impressions taken using different intraoral scanner (IOS) methods and CAD/CAM posts and cores produced based on these impressions in a fully digital workflow. Three different scanners were used in the study: Primescan, Trios 4, and Trios 4 scanspot. In this study, healthy, caries-free mandibular premolars extracted for therapeutic reasons were preferred. For each test model, one extracted premolar and two adjacent teeth were placed in a pink acrylic resin. The test models were scanned 12 times using a scanner, resulting in 180 IOS datasets. These data were compared with reference datasets generated by micro-CT imaging to assess the scanning accuracy. In addition, a total of 30 CAD/CAM posts and crowns, one each of zirconium dioxide (ZIR) and resin composite (COM) materials, were produced for each model and impression method. The fit accuracy of the posts and crowns was determined using an industrial scanner. In terms of scanning accuracy, the Primescan (PRI) method showed a statistically significantly lower accuracy than the Trios 4 (TRI) and Trios 4 + scanpost (TRI+SP +) methods. In terms of material comparison, posts and crowns made of zirconium dioxide (ZIR) showed higher fit accuracy than those made of resin composite. Within the limitations of this study, it was concluded that CAD/CAM posts and cores made of zirconium dioxide material may be preferable in terms of alignment accuracy in a fully digital workflow. It was also determined that the use of scan posts was not necessary with current IOS devices and that the use of scan posts resulted in lower alignment accuracy than when they were not used (38).

Vitai et al. conducted a comprehensive systematic review and network meta-analysis to compare the accuracy of different intraoral scanners (IOSs) in full-arch scans. This study aimed to evaluate the accuracy of intraoral scanners in different clinical scenarios (toothed, edentulous, implanted edentulous, and partially edentulous arches). A search of five databases in October 2021 resulted in 3,815 studies, of which 114 were eligible, and 53 were selected for the analysis. These studies compared the trueness and precision of the scanners with the reference STL files. In total, 26 different IOSs were evaluated. The accuracy of the IOSs for toothed, edentulous, and completely edentulous arches with implants was not significantly different from that of the reference scans. For partially edentulous and implanted arches, the accuracy of IOSs was significantly different from that of reference scans. Regardless of the clinical scenarios, significant differences in accuracy were observed between the IOSs. The accuracy of intraoral scanners in full-arch scans varies according to the clinical situation. Therefore, it is important to select the appropriate scanner for different arch types. This study emphasizes that the choice of digital scanners in dental practice should be customized according to the clinical situation (39).

Fukazawa et al. evaluated how accurately and consistently IOSs can measure abutment position. The study examined the measurement accuracy (trueness) and repeatability (precision) of intraoral scanners. Reference models were measured using a computerized numerical control coordinate measuring machine (CNCCMM) and these measurements were taken as a control group. Then, the reference models were measured using intraoral scanners and laboratory scanners, and the data obtained were evaluated with image analysis software. The results of the study showed that the measurement accuracy and repeatability of intraoral scanners varied depending on the type of scanner used and the size of the scan field. In particular, error rates were observed to increase when longer dental arches were scanned. These findings support the feasibility of using intraoral scanners in implant treatments. However, it is important to consider factors such as the choice of scanner and the size of the scan field to improve measurement accuracy (40). The accuracy of intraoral scanners is influenced by multiple factors beyond the scanner itself. Scanner-related characteristics, including image acquisition and processing algorithms, calibration procedures, resolution, and scanning technology, have been shown to affect scanning outcomes. In addition, clinical factors such as the scanning strategy, operator experience, scanning speed, moisture control, patient movement, and the extent of the scanned area may contribute to deviations in digital impressions. Environmental conditions and post-processing procedures, including software corrections and model generation workflows, can further influence the final accuracy of the digital model. These findings should be considered when selecting and using intraoral scanners in both clinical and research settings (11, 41, 42).

3. Conclusion

Intraoral scanners have become an integral part of modern digital dentistry and provide clinically acceptable accuracy for many restorative, implant, and orthodontic applications. The accuracy of these systems may vary depending on scanner technology, clinical conditions, and operator-related factors. Therefore, appropriate scanner selection, adherence to recommended scanning protocols, and adequate operator training are essential for obtaining reliable digital impressions and achieving predictable clinical outcomes.

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