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Accuracy of Dental Monitoring 3D digital dental models using photograph and video mode

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Introduction: This study aimed to test the accuracy of the 3-dimensional (3D) digital dental models generated by the Dental Monitoring (DM) smartphone application in both photograph and video modes over successive DM examinations in comparison with 3D digital dental models generated by the iTero Element intraoral scanner. **Methods:** Ten typodonts with setups of class I malocclusion and comparable severity of anterior crowding were used in the study. iTero Element scans along with DM examination in photograph and video modes were performed before tooth movement and after each set of 10 Invisalign aligners for each typodont. Stereolithography (STL) files generated from the DM examinations in photograph and video modes were superimposed with the STL files from the iTero scans using GOM Inspect software to determine the accuracy of both photograph and video modes of DM technology. **Results:** No clinically significant differences, according to the American Board of Orthodontics–determined standards, were found. Mean global deviations for the maxillary arch ranged from 0.00149 to 0.02756 mm in photograph mode and from 0.0148 to 0.0256 mm in video mode. Mean global deviations for the mandibular arch ranged from 0.0164 to 0.0275 mm in photograph mode and from 0.0150 to 0.0264 mm in video mode. Statistically significant differences were found between the 3D models generated by the iTero and the DM application in photograph and video modes over successive DM examinations. **Conclusions:** 3D digital dental models generated by the DM smartphone application in photograph and video modes are accurate enough to be used for clinical applications. (Am J Orthod Dentofacial Orthop 2019;156:420-8)

Teledentistry is one segment of telemedicine. Teledentistry is the combination of telecommunications and dentistry to provide more access to dental care, it involves the digital exchange of clinical information between a patient and a health care center or provider. Teledentistry can be used for remote dental consultation, treatment planning and monitoring, appliance fabrication, or on-site job training.[1-5]

Specific to orthodontics, teledentistry has been shown to be an effective method for positively identifying appropriate referrals, increasing treatment effectiveness, and saving time for both patients and orthodontists.[4] The main goal of teledentistry is to allow the orthodontist to maintain treatment control of patients who are unable to come into the office for regular visits. This is especially important in remote areas or where there is a shortage of providers and long waits for patients who have been appropriately referred.[5,6]

With the creation of smartphones, 2-way, real-time patient-doctor interaction is easier and more feasible than ever.[7] In the orthodontic field, text message applications, chat rooms, and e-mail reminders have been shown to improve oral hygiene as well as reduce treatment duration, bracket bond failure, and failed or late attendance.[4-8]

A recently invented technology (Dental Monitoring [DM]) allows orthodontists to monitor their patients remotely using a smartphone, using photographs or

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video scans taken by patients. Moreover, it can construct 3-dimensional (3D) digital models from these scans.[5,9]

With continuing advances in 3D digital imaging technology, conventional elastomeric impressions and dental stone casts are being replaced by digital impressions captured with intraoral scanners.[10,11] Digital models provide the advantage of not requiring disinfection, but also can be nondestructively modified for better examination of individual teeth. 3D mapping of tooth movement is achievable by superimposing digital models on stable structures with 3D software systems.[12-14]

With the trend toward digital impressions, recent studies have focused on evaluating the accuracy of digital scanners.[15-18] Digital impressions captured by intraoral scanners have been shown to be as accurate in both trueness and precision as conventional elastomeric impressions, and thus are acceptable for clinical use.[16-18] Numerous studies have tested the accuracy of full-arch iTero (Align Technology, San Jose, Calif)-generated digital models and demonstrated good results.[19-23]

Over the past decade, increasing numbers of adults aged 18 years or older have sought orthodontic treatment[24]; this has resulted in a correspondingly greater demand for more esthetic and invisible orthodontic appliances.[25] Analyses of hundreds of thousands of Invisalign cases show that the iTero scanner works better with the Invisalign workflow than with traditional polyvinyl siloxane impressions.[26]

The objective of this study was to compare the accuracy of 3D digital dental models generated from the smartphone application in photograph and video modes with 3D digital dental models generated from the iTero Element intraoral scanner. The null hypothesis was that there would be no statistically significant mean differences in global deviations when comparing 3D digital dental models generated by the smartphone application in photograph and video modes with the 3D digital dental models generated by the iTero Element intraoral scanner over successive smartphone photograph and video examinations.

MATERIAL AND METHODS

DM (Paris, France) is a digital technology software.[27] DM technology allows orthodontists to monitor their patients remotely using a smartphone, using photographs or video scans taken by patients. DM comprises 3 interconnected platforms: a smartphone application for patients, a patented tooth movement tracking algorithm, and an online Doctor Dashboard on which orthodontists can view patient treatment progress and pretreatment or posttreatment changes. To use the Doctor Dashboard, the orthodontist first uploads an initial 3D digital model in stereolithography (STL) file format. The patient then takes a pretreatment video or photograph examination with a DM-patented cheek retractor, using the DM application on their own smartphone (Fig 1, *A*). DM uses the initial scan and pretreatment video or photograph examination to establish a baseline of tooth position and occlusion from which to calculate future movements. Successive DM examinations then use the immediately preceding 3D model to perform calculations to produce the next 3D model.[5]

Ten typodonts were set up in class I anterior crowding wax forms. All occlusion screws on the typodont occluders were adjusted to stabilize the occlusion of the maxillary and mandibular arches and the associated forces that could result in unwanted tooth movements within the wax.

Each of the 10 models was scanned with the iTero Element intraoral scanner according to the manufacturer's instructions. The scans were exported from the MyAligntech online account as separate open source STL files for the maxillary and mandibular arches. The STL files were then uploaded to the DM platform as the initial 3D reference model for each typodont from which the next 3D model would be generated. The same STL file was also sent to Align Technology through the Invisalign Doctor site, with instructions to align teeth and resolve crowding as much as possible in 10 sets of maxillary and mandibular aligner trays without using attachments or moving posterior teeth. After scanning, initial photograph and video examinations for each typodont were done using the DM mobile application (version 2.38) on an iPhone 7, model A1660 (Apple, Cupertino, Calif), running iOS 11.2. The initial iTero scans were compared with the DM photograph and video records to ensure that there were no STL file errors from the iTero scan or inadvertent tooth movements from handling the typodonts during the scanning and capturing examination.

The first of 10 maxillary and mandibular Invisalign trays were then seated onto each typodont and the typodonts were placed in a Polystat Immersion Circulator hot water bath (Fisherbrand; Fisher Scientific, Waltham, Mass) at 45°C for 5 minutes. On removal from the water bath, light pressure was applied manually to ensure that the maxillary and mandibular trays were fully seated to achieve the planned tooth movement. The typodonts were cooled for 15 minutes at room temperature to reharden the wax and stabilize the teeth in their new positions before removing the Invisalign trays. Each typodont was then scanned using the iTero Element intraoral scanner as tray 1. Photograph and video

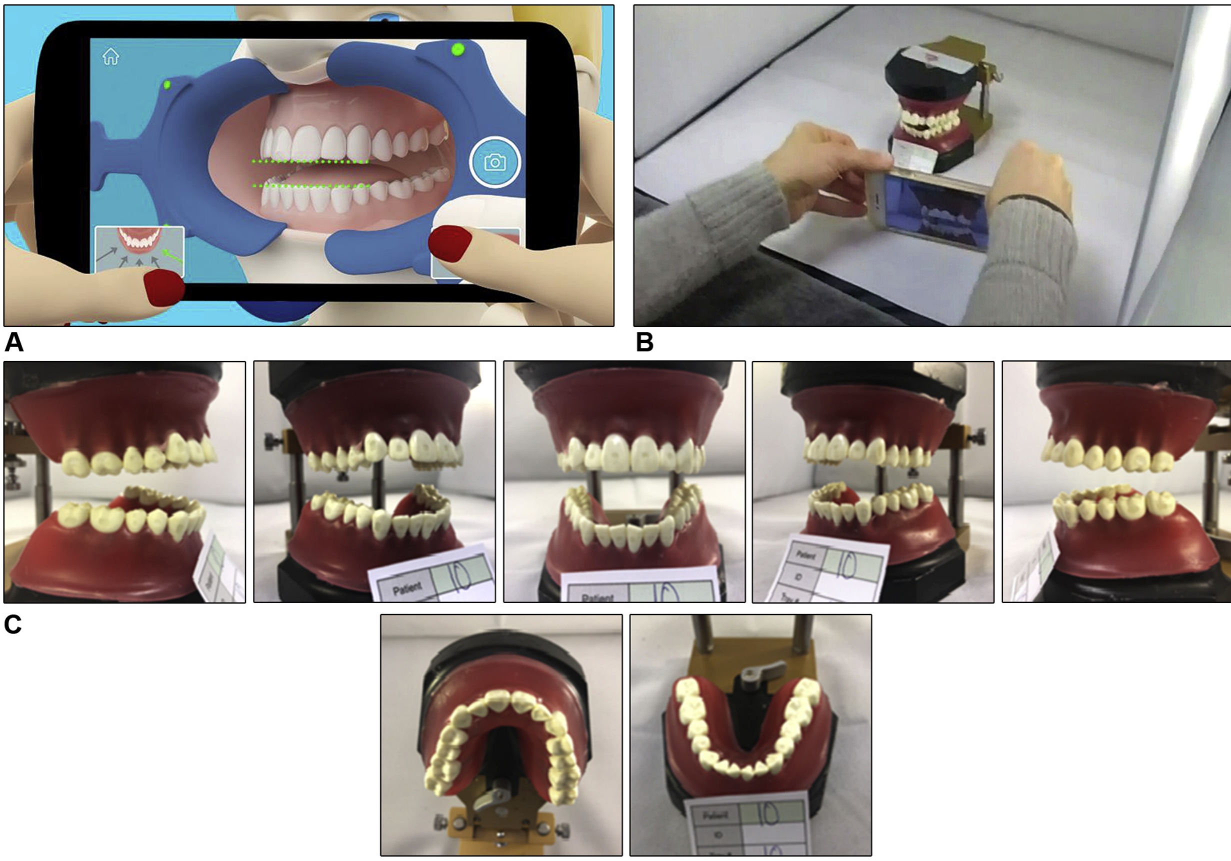

Fig 1. A, Dental Monitoring smartphone application. **B,** Operator scanning the model with the smartphone. **C,** Photograph scans.

examinations using the DM application were also captured as described for each typodont (Fig 1).

This process was repeated for all 10 sets of maxillary and mandibular Invisalign trays for each of the 10 typodonts and labeled as Invisalign trays 1-10.

Each photograph examination consisted of 7 photographs: right posterior, right canine, center, left canine, left posterior, maxillary occlusal, and mandibular occlusal. Each video examination consisted of 3 videos (6 seconds long): right posterior to the left canine, right canine to left posterior, and maxillary occlusal to mandibular occlusal. All examinations were taken against a white background under controlled lighting conditions for standardization. All examinations were captured by the same operator utilizing 2 iPhone 7 mobile devices, 1 with the DM mobile application locked in photograph mode and the other locked in video mode.

Two operators performed the typodont scanning using 2 iTero Element intraoral scanners that were calibrated to the same settings. 3D image STL files were generated from the DM scans in photograph and video modes and from the iTero Element scans for each typodont after each tray. Separate files were generated for the maxillary and mandibular arches. Three sets of maxillary and mandibular arch trays were excluded because of quality control errors. Thus, 97 maxillary arch and 97 mandibular arch files from the DM photograph and video examinations and the iTero Element scans were generated for this study.

Data were collected from the Dental Monitoring Research and Development headquarters in Montreuil, France, but processed and analyzed at the University of Illinois, College of Dentistry, in Chicago, Ill. The 3D image STL files generated from the DM scans in photograph and video modes were superimposed on the STL files generated from the iTero Element scans for each tray of every typodont to compare the differences in geometric shape. The simulated gingiva in the model was removed from the DM STL files so that only the maxillary and mandibular teeth remained. This allowed more accurate global deviation calculation by removing any error introduced by the unwanted movement of the

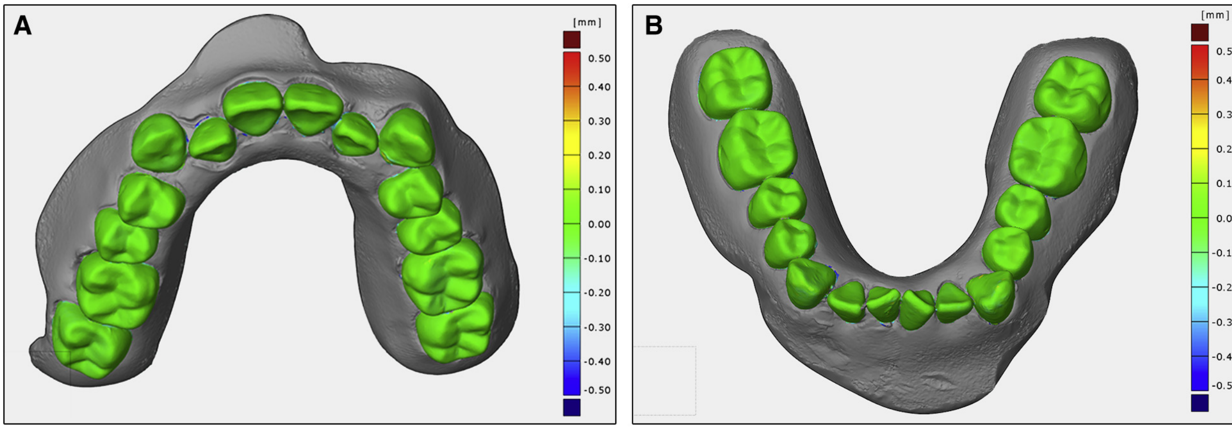

Fig 2. **A,** Maxillary and **B,** mandibular examples of heat maps created from the superimposition of the 3D digital models generated from the DM photographs/video scans on the 3D digital models generated from the iTero Element scans.

Table I. Average global deviation values in photograph mode

Maxillary arch (mm)	*Mandibular arch (mm)*	*Combined (mm)*
0.0212	0.022	0.0216

simulated gingiva during handling of the typodonts. The differences between the DM- and iTero Element-generated 3D models were measured using GOM Inspect (GOM, Braunschweig, Germany) 3D evaluation software to obtain a global deviation, measured in millimeters, from over 200,000 surface data points. The global deviation is the overall best-fit alignment of the individual tooth positions between the 2 digital models. The software calculates global deviation using a prealignment calculation. According to the GOM manual, "Pre-alignment aligns the actual data (measurement, meshes...) automatically to the nominal data, independently of start positions. A pre-alignment can be carried out with subsequent automatic best-fit alignment."[28]

Professional standards established by the American Board of Orthodontics (ABO) objective grading system consider deviations of <0.5 mm for alignment and marginal ridge categories to be clinically acceptable,[29] and, according to the previous study, 0.5 mm is of minimal clinical significance when investigating the accuracy of Invisalign-predicted tooth movements utilizing software similar in function to GOM Inspect.[30] Because the software is capable of detecting deviations that are less than what is clinically relevant, maximum and minimum deviation threshold values of 0.5 and −0.5 mm were chosen. A heat map was generated for each superimposition to show discrepancies ranging from 0.5 to −0.5 mm in areas of expansion and contraction of the DM 3D digital model compared with the iTero model. Deviations of >0.5 mm or <−0.5 mm appear gray in the heat map (Fig 2).

Exploratory data analysis was performed using SPSS (IBM SPPS for Windows, version 22.0; IBM Corp, Armonk, NY) to investigate whether there were any statistically significant mean differences in global deviations between 3D digital dental models generated by the DM application in photograph and video modes and the 3D digital dental models generated by the iTero Element over successive DM photograph and video examinations. Descriptive statistics (mean, SD, 95% confidence interval [CI] of the mean) along with graphic displays were used for mean deviation comparisons. The Shapiro-Wilk test was carried out to determine the data distribution.

RESULTS

The assumption of normality of the data using the Shapiro-Wilk test showed that all variables are normally distributed.

In photograph mode, global deviations in the maxillary arch averaged 0.0212 mm, the mandibular arch averaged 0.022 mm, and that of the maxillary and mandibular arches combined was 0.0216 mm (Table I). The mean deviations were all <0.5 mm and thus were not clinically significant. Differences in global deviations throughout successive DM photograph examinations were averaged for all 10 typodonts at each tray. Maxillary arch 95% CI comprised values of 0.0119-0.0293 mm; mandibular arch 95% CI comprised values of 0.0084-0.0299 mm (Tables II and III). The 95% CI

Table II. Maxillary arch mean, SD, and 95% CI over successive DM photograph examinations

	Invisalign maxillary arch (mm)									
Trays	*Tray 1*	*Tray 2*	*Tray 3*	*Tray 4*	*Tray 5*	*Tray 6*	*Tray 7*	*Tray 8*	*Tray 9*	*Tray 10*
Descriptive mean	0.0149	0.0163	0.0174	0.0198	0.0208	0.0222	0.0239	0.0238	0.0249	0.0258
SD	0.0036	0.0033	0.0027	0.0046	0.0034	0.0032	0.0032	0.00263	0.0041	0.0024
95% CI	0.0119-0.0179	0.0014-0.0187	0.0146-0.0183	0.0162-0.0233	0.0184-0.0233	0.0183-0.0247	0.0216-0.0262	0.0219-0.0256	0.0218-0.0281	0.0258-0.0293

Table III. Mandibular arch mean, SD, and 95% CI over successive DM photograph examinations

	Invisalign mandibular arch (mm)									
Trays	*Tray 1*	*Tray 2*	*Tray 3*	*Tray 4*	*Tray 5*	*Tray 6*	*Tray 7*	*Tray 8*	*Tray 9*	*Tray 10*
Descriptive mean	0.0221	0.0164	0.0170	0.0194	0.0195	0.0215	0.0234	0.0244	0.0276	0.0275
SD	0.0164	0.0031	0.0032	0.0032	0.0037	0.0044	0.0028	0.0024	0.0030	0.0033
95% CI	0.0085-0.0358	0.0142-0.0187	0.0148-0.0193	0.0167-0.0221	0.0168-0.0221	0.0183-0.0246	0.0214-0.0255	0.0227-0.0261	0.0253-0.0299	0.0252-0.0299

Table IV. Range of mean, SD, and 95% CI over successive DM photograph examinations

Arch	*Maxillary arch (mm)*	*Mandibular arch (mm)*
Descriptive mean	0.0149-0.0276	0.0164-0.0275
SD	0.0023-0.0044	0.0116-0.0044
95% CI	0.0119-0.0293	0.0084-0.0358

of the mean differences in global deviations for each tray indicated that these differences were statistically significant (P <0.05) (Table IV). However, because all global deviations were <0.5 mm, this finding was not clinically significant. Graphic displays show a positive trend for both maxillary and mandibular arches over successive DM photograph examinations (Fig 3). The preliminary global deviation of 0.0609 mm in the first tray of patient 2 skews this trend initially. No statistically significant differences existed between the maxillary and mandibular arches.

In video mode, the global deviations for the maxillary arch averaged 0.0202 mm; the global deviations for the mandibular arch averaged 0.0205 mm. The mean global deviation for maxillary and mandibular arches combined was 0.0204 mm (Table V). Differences in global deviations throughout successive DM video examinations were averaged for all 10 typodonts at each tray. For the maxillary arch, the 95% CI included values ranging from 0.0112 to 0.0273 mm. The mandibular arch 95% CI included values ranging from 0.0115 to 0.0290 mm (Tables VI, VII and VIII; Fig 4). The 95% CI of the mean differences in global deviations for each tray indicated that these differences were statistically significant (P <0.05). However, the global deviations were not clinically significant because all values were <0.5 mm. Graphic displays showed a positive trend for both maxillary and mandibular arches over successive DM video examinations (Fig 4). No statistically significant differences existed between the maxillary and mandibular arches. The increased mean global deviation for both arches was approximately the same over successive DM examinations.

Trend lines of the mean global deviation values of maxillary and mandibular arches were generated for photograph and video modes by plotting the mean global deviation values for all 10 typodonts at each step of Invisalign tray. The maxillary arch trend line equation in photograph mode was $y = 0.0013x + 0.0138$, and the mandibular arch equation was $y = 0.0012x + 0.0153$. The maxillary arch trend line equation in video mode was $y = 0.0013x + 0.0128$, and the mandibular arch equation was $y = 0.0013x + 0.0131$. To determine when clinical significance may be reached throughout successive DM photograph and video examinations, 0.5 mm was substituted for "y" in the preceding equations. This resulted in a projected clinical significance in photograph mode after 374 successive photograph examinations in the maxillary arch and 403 photograph examinations in the mandibular arch. For video mode, clinical significance may be reached after 375 successive upper arch and lower arch DM video examinations have been captured for each typodont.

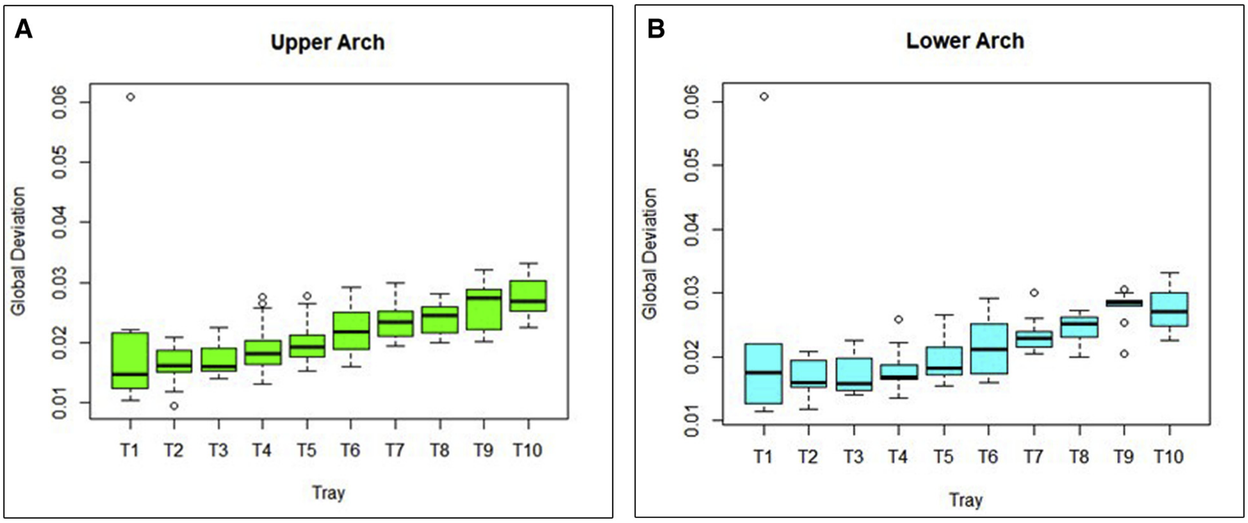

Fig 3. A, Maxillary and **B,** mandibular arch means, SD, and 95% CI over successive DM photograph examinations.

Table V. Average global deviation values in video mode

Maxillary arch (mm)	*Mandibular arch (mm)*	*Combined mean (mm)*
0.0202	0.0205	0.0204

DISCUSSION

This study aimed to determine the accuracy of the 3D digital dental models generated by the DM application in photograph and video modes compared with the 3D models generated by the iTero. There were no statistically significant mean differences in global deviations among the studied groups. This finding indicates that 3D digital dental models generated by the DM application in photograph and video modes were comparable with the 3D digital dental models generated by the iTero Element intraoral scanner. Moreover, the results showed that average differences between DM- and iTero Element-generated 3D models were 0.021 mm for photographs and 0.020 mm for video mode, suggesting clinical insignificance. Professional standards established by the ABO objective grading system consider deviations of <0.5 mm to be clinically acceptable.[29]

The results also showed that the mean global deviation gradually increased from tray 1 to tray 10 in both arches of all studied typodonts using DM in both photograph and video modes. The 95% CI of the mean global deviation differences indicated statistical significance for all trays (P <0.05). However, these differences were not clinically significant because all values were <0.027 mm.[29,30] Each typodont was also scanned a second time after the final set of trays, before and after the photograph and video examinations were taken, to account for errors introduced while handling the typodonts. The deviation between these 2 scans for both arches in all 10 typodonts had an overall mean of 0.0330 mm. These deviations were within the range of precision, 0.02984-0.1039 mm, of the iTero scanner for full-arch scanning found in previous studies.[10,15,22,23,31] Therefore, any errors that may have been introduced while scanning the typodonts with the iTero and capturing the DM examinations were insignificant.

The clinical significance of remote 3D monitoring is that it could be especially useful to increase access to care for patients who live in remote areas or commute long distances to receive orthodontic treatment. The average orthodontic patient appointment interval is 4 to 6 weeks.[32] With technology such as the DM application, orthodontists can remotely monitor patients for scheduling optimization and possibly treat patients with higher efficiency. The default DM examination is scheduled for every 2 weeks, but the intervals can be customized for each patient to accommodate the need of oral hygiene or monitoring of elastic wear. More frequent monitoring and communication with these patients may enhance motivation and cooperation.

Because most clear aligners, customized fixed appliances, and customized orthodontic archwires depend on 3D digital models, intraoral self-scanning by smartphones may reduce the cost and chairtime needed for the scanning process. If there is a discrepancy between actual and planned tooth movement, the refinement

Table VI. Maxillary arch mean, SD, and 95% CI over successive DM examinations in video mode

Trays	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9	Tray 10
	Invisalign maxillary arch (mm)									
Descriptive mean	0.0148	0.0156	0.0165	0.0172	0.0192	0.0201	0.0231	0.0241	0.0248	0.0256
SD	0.0043	0.0033	0.0026	0.0028	0.0029	0.0024	0.0024	0.0026	0.0035	0.0023
95% CI	0.0112-0.0184	0.0133-0.0180	0.0146-0.0183	0.015-0.0193	0.017-0.0212	0.0184-0.0218	0.0214-0.0248	0.0222-0.0260	0.022-0.0273	0.0239-0.0272

Table VII. Mandibular arch mean, SD, and 95% CI over successive DM examinations in video mode

Trays	Tray 1	Tray 2	Tray 3	Tray 4	Tray 5	Tray 6	Tray 7	Tray 8	Tray 9	Tray 10
	Invisalign mandibular arch (mm)									
Descriptive mean	0.0150	0.0167	0.0162	0.0194	0.0195	0.0215	0.0241	0.0240	0.0256	0.0264
SD	0.0041	0.0038	0.0023	0.0032	0.0036	0.0026	0.0030	0.0039	0.0025	0.0037
95% CI	0.0115-0.0184	0.0135-0.0198	0.0136-0.0180	0.0167-0.0221	0.0165-0.0224	0.0193-0.0236	0.0216-0.0266	0.0206-0.0272	0.0235-0.0277	0.023-0.0291

Table VIII. Range of mean, SD, and 95% CI over successive DM examinations in video mode

Arch	Maxillary arch (mm)	Mandibular arch (mm)
Descriptive mean	0.0148-0.0256	0.0150-0.0264
SD	0.0023-0.0043	0.0021-0.0041
95% CI	0.0112-0.0272	0.0115-0.0290

visit could be scheduled for optimal clinical outcome. Oral hygiene and compliance also could be improved by these applications. In the future, intraoral scans could theoretically be achieved remotely with this technology by having DM generate a 3D STL file from patient-administered photograph or video examinations rather than requiring an additional office visit.

In this study, we demonstrated the accuracy of DM technology to be as accurate as the iTero Element, although more studies in vivo are warranted to confirm the results. There may be potential for fabrication of appliances, such as Essix retainers, from patient-administered DM photograph or video examination alone. This would eliminate time and travel for in-office appointments for impressions, as well as reducing office chairtime and material expense.[33] Remote monitoring can enhance practice efficiency because the orthodontist can notify patients about treatment progress and problems before in-person appointments.

Finally, DM has the potential to be a source of data for research in the orthodontic field. Since this technology quantifies and tracks tooth movements at specific intervals of time, it could be used to determine the optimal time interval between appointments during each stage of treatment. It also may be possible to evaluate the efficiency and effectiveness of new and existing appliances and products in ways that could not be achieved in the past.

Live patients are instructed to take the first photograph and video examination with teeth in occlusion. However, to avoid inadvertent movement of the typodont teeth from forces of occlusion, in this study no photograph or video examinations were taken with the typodonts in occlusion. Therefore, this study cannot assess the ability of DM to accurately track interocclusal relationships.

In addition, because this study was performed using only class I malocclusion with mild crowding, and all teeth fully erupted and visible in the arches, the accuracy of DM tooth tracking cannot be assumed for all types of malocclusions and dental problems.

Because this study captured DM examinations after each Invisalign tray, it only investigated DM's accuracy in tracking small tooth movements.[34] In vivo studies are warranted to test the accuracy of DM when other factors come into play, such as saliva, plaque and calculus, teeth with various restorations, and limited mouth opening. Studies verifying the ability of DM to accurately record patient occlusion, including functional shifts, are also recommended. In our study, scans were carried out by professionals on typodonts without lips or cheeks. The ability of patients to accurately capture images of their own teeth with standard smartphones needs to be examined. It is claimed that DM, using a cone-beam computed tomography scan for the initial scan,

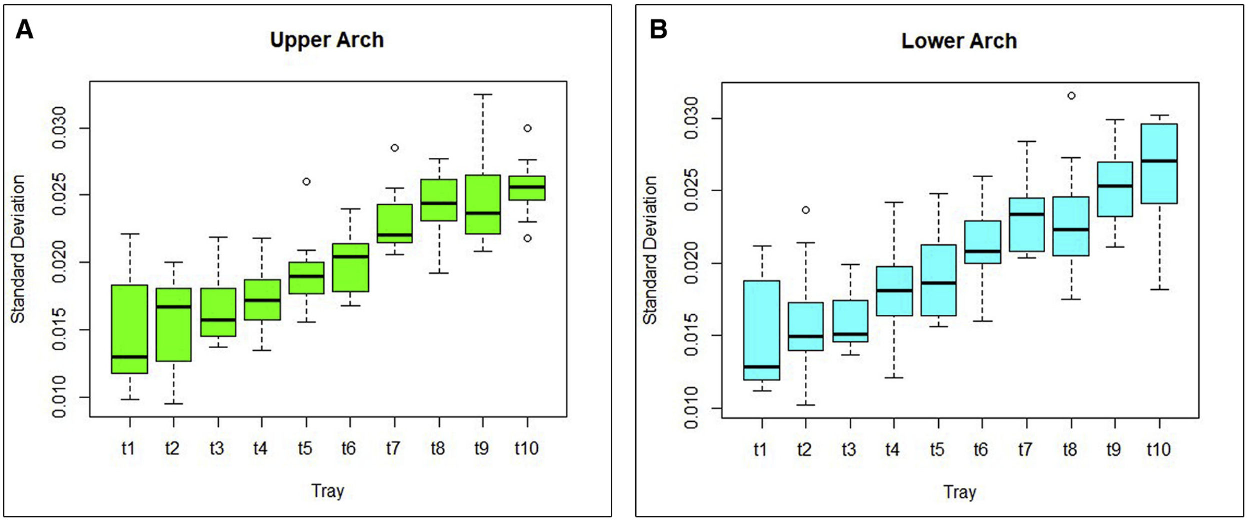

Fig 4. **A,** Maxillary and **B,** mandibular arch means, SD, and 95% CI over successive DM video examinations.

allows for the tracking of root movements. If accurate, root tracking could possibly allow orthodontists to preplan their bracket positioning. However, future studies that test the validity of this claim need to be performed before orthodontists rely on this functionality.

CONCLUSIONS

1. 3D digital dental models generated by the DM smartphone's application scans from photograph and video modes are comparable to iTero scans and are accurate enough to be used in clinical applications.
2. Based on the trends displayed in this study, it was predicted that deviations would not reach clinical significance of 0.5 mm according to ABO-determined standards until 374 successive DM photograph examinations in the upper arch and 403 examinations in the lower arch have been captured. Clinical significance was predicted to be reached after 375 successive extraoral DM video examinations have been captured for both upper and lower arches.
3. Intraoral examination and other factors in vivo may lead to larger deviations that cause DM examination to reach clinical significance earlier than the results shown in this study.

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