THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Accuracy of three digital workflows for implant abutment and crown fabrication using a digital measuring technique

Stephanie Zeller, DDS, MS,[a] David Guichet, DDS,[b] Elias Kontogiorgos, DDS, PhD,[c] and William W. Nagy, DDS[d]

ABSTRACT

Statement of problem. The accuracy of a full digital workflow using an Atlantis abutment and a milled zirconia crown; a full digital workflow with a 3Shape split-file workflow using a zirconia abutment and crown; and an interrupted digital workflow using an Atlantis abutment and a milled zirconia crown is unclear.

Purpose. The purpose of this in vitro study was to compare 2 full digital workflows relative to an interrupted workflow for restoring an implant with a custom abutment and crown. The secondary purpose of this study was to validate a digital means of measuring internal fit and marginal discrepancy using engineering software programs.

Material and methods. Three workflows were evaluated. The first group, interrupted digital Atlantis (IDA) workflow, included a customized Atlantis abutment that was designed, received, and then rescanned for the definitive crown design. The second group, full digital Atlantis (FDA) workflow, included a customized Atlantis abutment and its corresponding standard tessellation language (STL) file, the Atlantis Core File, which was immediately imported into design software and used for crown design and milling. The third group, full digital split-file (FDSF) workflow, used 3Shape's full digital workflow for abutment and crown design called the split-file workflow, in which the crown and abutment were designed and milled simultaneously. All restorations were evaluated with standardized measurements using a scanning electron microscope (SEM) for 2D measurements, followed by standardized measurements using Geomagic Control, an engineering software program, which facilitated 3D evaluations of the specimens.

Results. The 2 Atlantis workflows, IDA and FDA, had statistically smaller marginal openings (P=.002) than the FDSF when measured using 2D SEM. The FDA had a statistically smaller 2D SEM marginal gap than the other 2 groups, IDA (P=.002) and FDSF (P=.002). The FDA had a statistically smaller 3D Geomagic marginal gap than the other 2 groups, IDA (P=.004) and FDSF (P=.006). The FDSF had a statistically smaller 3D Geomagic internal fit than the other 2 groups, FDA and IDA (both P=.006).

Conclusions. All 3 workflows evaluated in this study showed clinically acceptable results in terms of mean marginal gap below 120 μm. The SEM evaluation of mean marginal opening revealed that IDA and FDA mean marginal openings were statistically smaller than the FDSF mean marginal opening. SEM and Geomagic measurements revealed that the FDA mean marginal gap was significantly smaller than IDA and FDSF mean marginal gaps. Geomagic evaluation of mean internal fit revealed that the FDSF was significantly smaller than IDA and FDA. The use of Geomagic to measure and evaluate mean marginal gap and mean internal fit as defined in this study proved to be an acceptable form of measurement with statistical validation. (J Prosthet Dent 2019;121:276-84)

Computer-assisted design and computer-assisted manufacturing (CAD-CAM) has gained widespread acceptance and use in implant dentistry, with accuracy that rivals conventional techniques for prosthesis and abutment fabrication.[1-4] Digital workflows can be more time-efficient than conventional analog workflows, reducing clinical chair time and laboratory manufacturing steps.[5]

Funding: This study was supported in part by a Stanley D. Tylman Research Grant from the American Academy of Fixed Prosthodontics and Department of Restorative Dentistry, Texas A&M University College of Dentistry. Neither of the funding sources had any role in study design; in the collection, analysis, and interpretation of data; or in the writing of the report.

[a]Private practice, Seattle, Wash.
[b]Private practice, Orange, Calif.
[c]Director of Implant Dentistry, Department of Restorative Sciences, Texas A&M University College of Dentistry, Dallas, Texas.
[d]Previous Professor and Graduate Program Director, Department of Restorative Sciences, Texas A&M University College of Dentistry, Dallas, Texas.

Clinical Implications

The three workflows evaluated in this study were clinically acceptable and can therefore be used with confidence to achieve acceptable fit for single implant-supported crowns and abutments. In addition, Geomagic with the digital silicone replica technique is acceptable for measuring marginal discrepancy.

Current technology allows clinicians to fully customize implant abutments to match clinical situations.[1,4,6] In ordering customized titanium Atlantis (Atlantis; Dentsply Sirona) abutments, the digital design of the Atlantis abutment as a standard tessellation language (STL) file, called an Atlantis Core File, can be viewed and manipulated through an editor on the Atlantis Web interface, and an STL file of the definitive abutment design can be requested (www.dentsply.com).[7,8] The Core File can be imported into design software and used to proceed with crown designing and milling. The customized Atlantis abutment and milled crown can then be delivered to the patient in 1 appointment.

Two-piece abutments with a titanium base cemented into a zirconia abutment have been shown to be more successful than 1-piece zirconia abutments.[8] Gehrke et al[8] found 2-piece zirconia abutments that demonstrated greater resistance to fracture than 1-piece and stock zirconia abutments. Titanium-base zirconia abutments offer a more reliable alternative to 1-piece zirconia abutments in esthetically demanding situations in which zirconia is preferred over titanium.

With the advent of 2-piece titanium-base abutments, the customized zirconia abutment and a zirconia crown can be milled in office, which presents the potential for an in-office full digital workflow. The 3Shape (3Shape Dental System) software offers the split-file workflow that facilitates abutment and crown designing simultaneously from 1 initial scan of the implant location.[9] The crown and abutment can then be milled and, without clinical evaluation or rescanning, be delivered to the patient in a single visit. Sheridan et al[9] evaluated the split-file workflow against several more conventional interrupted workflows and found that, after adjustments, the completely digital workflow produced clinically acceptable results.

The accuracy of full digital workflows can be assessed by evaluating the fit of the implant abutment to the implant crown. Various studies have indicated that a suggested marginal discrepancy of 120 μm or less is required for high probability of clinical success for ceramic restorations.[10-12] Martinez-Rus et al[12] used 120 μm as the acceptable marginal opening for ceramic crowns on abutments based on findings in previous studies.[12]

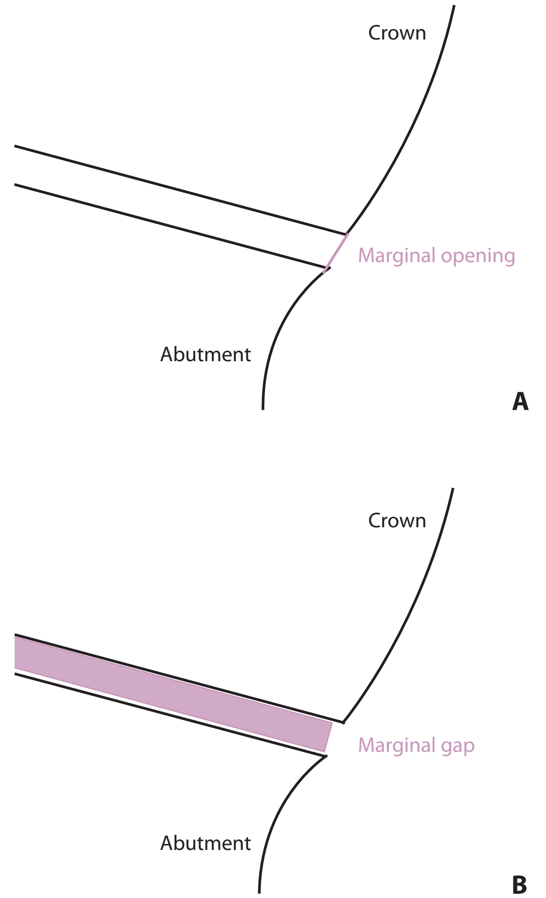

Figure 1. Measured values. A, Marginal opening. B, Marginal gap.

Several methods have been used to measure marginal discrepancy. Groten et al[13] determined that a minimum of 50 measurements are required to determine marginal discrepancy. Digital measuring procedures have been used to digitally measure the distance between an intaglio crown surface and its die or abutment, either just at the margin to measure marginal discrepancy or over the entire abutment and crown intaglio surface to evaluate internal fit.[2,14-21]

The digital silicone replica technique is based on the conventional silicone replica technique.[2,16-19,22] The digital technique is accomplished first by scanning the die and then by scanning the same die with a silicone replica fixed; then, the 2 scans are digitally overlaid and used to measure internal fit. As part of this study, a digital measuring protocol was developed from previously reported protocols and then validated using measurements obtained from a scanning electron microscope (SEM), which had also been previously validated.[9,23,24]

The purpose of this study was to compare 2 full digital workflows with a more customary interrupted workflow that included a secondary scan of the custom abutment

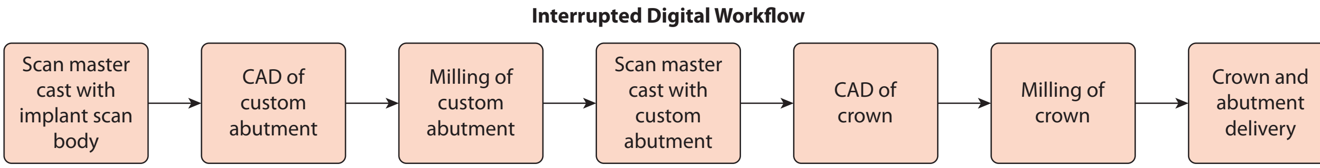

Figure 2. Interrupted digital Atlantis workflow. CAD, computer-aided design.

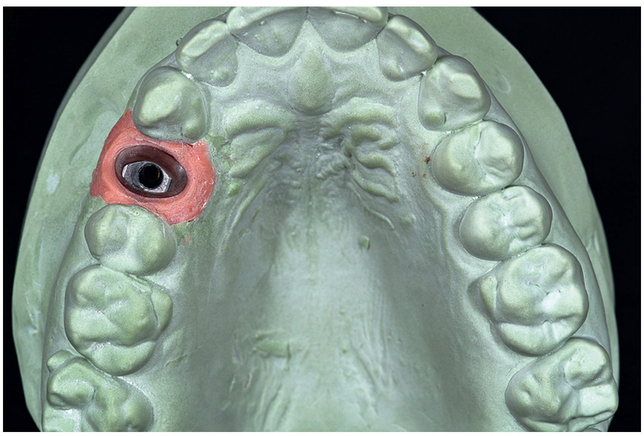

Figure 3. Atlantis abutment in definitive cast.

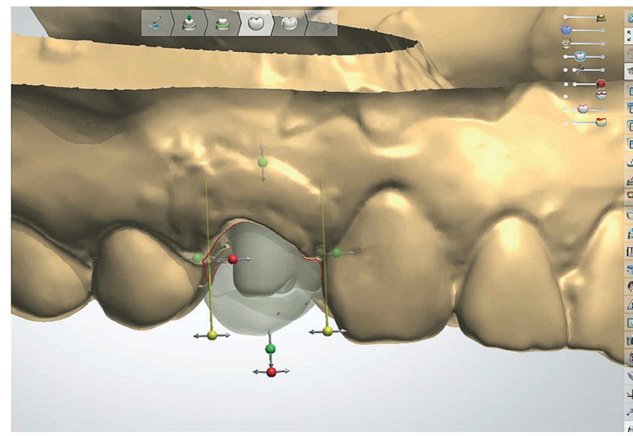

Figure 4. Interrupted digital Atlantis workflow. Digital crown design with abutment visualization.

before definitive crown design. A secondary purpose of this study was to use and validate a digital means of measuring internal fit and marginal gap with an engineering software program (Geomagic Control 2015; 3D Systems). For the purposes of the study, internal fit was defined as an average of the distance measured between the crown intaglio and abutment surface. Marginal opening was defined as the distance from crown to abutment measured from the outermost part of the margin (Fig. 1A). Marginal gap was defined as an average distance from the crown intaglio to the abutment surface across the entire preparation margin (Fig. 1B). The null hypothesis was that no difference would be found in internal fit, marginal gap, and marginal opening among the 3 groups.

MATERIAL AND METHODS

A single definitive cast was fabricated with an implant analog in the maxillary right first premolar position from a definitive impression with a custom impression post with the desired emergence profile of the soft tissue. A conical implant of dimension 4.2×11 mm (Astra Tech EV; Dentsply Sirona) and its corresponding analog were used. Scans were acquired using a laboratory scanner (3Shape D900; 3Shape).

Three different workflows were designed and compared. All crowns were designed using 3Shape's default settings for zirconia copings and were milled using a 5-axis mill (M1; Zirkonzahn GmbH), from green-stage zirconia (Prettau; Zirkonzahn GmbH), then sintered according to the manufacturer's specifications.

The first group, interrupted digital Atlantis (IDA) workflow, represented the most used workflow, which included a customized Atlantis abutment that was designed and received and then rescanned for definitive crown design (Fig. 2). First, an implant scan body (Atlantis; Dentsply Sirona) was secured into the definitive cast implant analog and digitized using the scanner. An STL file of the cast was sent to Atlantis for custom abutment fabrication. The abutment was designed and customized through the Atlantis Web interface editor, and 14 abutments of the single design were requested. Half (n=7) of the requested abutments were used for the IDA group, and the other half (n=7) were used for the second group, full digital Atlantis (FDA) workflow. Once the 7 abutments for the IDA group were received, they were placed in the definitive cast and individually rescanned for crown design and fabrication (Fig. 3). One zirconia crown with a facial cutback was designed for each of the 7 abutments and then sent for milling (Fig. 4).

The FDA group included a customized Atlantis abutment and its corresponding STL file, the Atlantis Core File, which was immediately imported into the design software and used for crown designing and milling (Fig. 5). As previously described, after scanning the cast and implant scan body, the STL file of the implant in the definitive cast was sent to Atlantis for custom

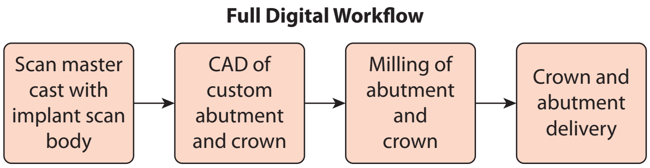

Figure 5. Full digital Atlantis and full digital split-file workflows. CAD, computer-aided design.

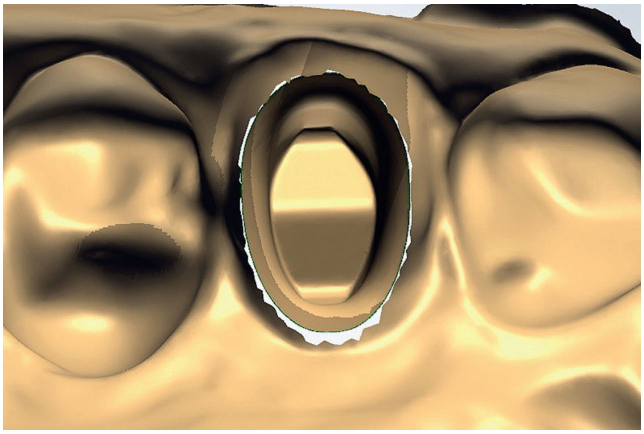

Figure 6. Atlantis core file abutment imported into 3shape design software.

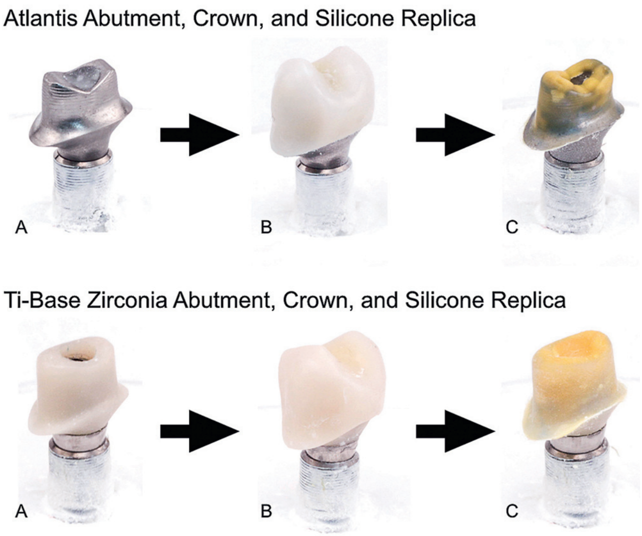

Figure 7. Creation of silicone replica cement gap. A, Abutment secured with screw into stone base and scanned. B, Abutment coated with PVS adhesive and crown filled with PVS and seated onto abutment with 22 N of standardized load for 10 minutes. C, Crown removed from abutment, leaving PVS replica adhered to abutment and abutment with PVS replica scanned. PVS, polyvinyl siloxane.

abutment fabrication. The abutment was customized through the Web interface, and 14 abutments of the single design were requested. Once the abutment design had been finalized, the Atlantis Core File, an STL file of the customized Atlantis abutment, was imported into the 3Shape design software, allowing for immediate crown design (Fig. 6). A custom zirconia crown was then designed, and 7 zirconia crowns were milled from the single STL file design.

The third group, full digital split-file (FDSF) workflow, used the 3Shape's full digital workflow for abutment and crown design called the split-file workflow. A scan body (Biodenta) was placed in the definitive cast and scanned using the 3Shape D900. 3Shape's split-file workflow was used, in which the zirconia abutment and crown were designed consecutively from the single scan (Fig. 5).[10] Once designed, the zirconia abutment and zirconia crown were exported as STL files and sent to the milling unit. From the single STL files, 7 zirconia abutments and crowns were milled. Titanium-base zirconia abutments were composed of titanium bases provided by Biodenta (Hybrid Ti-Base; Biodenta) and zirconia abutments milled using a 5-axis mill (M1) from zirconia blocks (Translucent; Zirkonzahn GmbH).

Specimens were prepared for measuring by creating a silicone replica of the cement space on the abutment (Fig. 7). A stone base (Mounting Stone; Whip Mix Corp) was fabricated securing the Astra Tech EV conical implant of dimensions 4.2×11 mm. The stone base included markers that could later be used in the software to overlay the scans. Before securing the abutment, the surface area below the finishing line of the abutment was slightly roughened by airborne-particle abrading with 25-μm aluminum oxide at 100 kPa pressure to reduce reflectivity and eliminate the need for a coating spray on the base between scans. The abutment was then secured to the base by tightening the abutment screw. To achieve an accurate scan above the finishing line of the abutment, the reflective surface had to be altered. Several different sprays were tested on abutments to evaluate consistency in each spray and thickness of the spray before one was selected. The abutment surface above the finishing line was then coated with a light spray (Foot Powder Spray; Walgreens) to reduce reflectivity and then scanned using the 3Shape D900. Once scanning was completed, the abutment and the abutment's corresponding crown were cleaned with alcohol then dried. The abutment was then coated with a thin layer of polyvinyl siloxane (PVS) adhesive (Vinyl Polysiloxane Adhesive; Kerr Corp) and allowed to dry. Then, the crown was filled with light-body PVS (Light Body Wash; Kerr Corp) and then seated onto the secured abutment with firm finger pressure as the excess PVS was quickly removed. The crown-abutment unit was then placed under 22 N of standardized load for 10 minutes. Once polymerization was complete, the crown was quickly removed from the abutment, leaving the internal space PVS replica

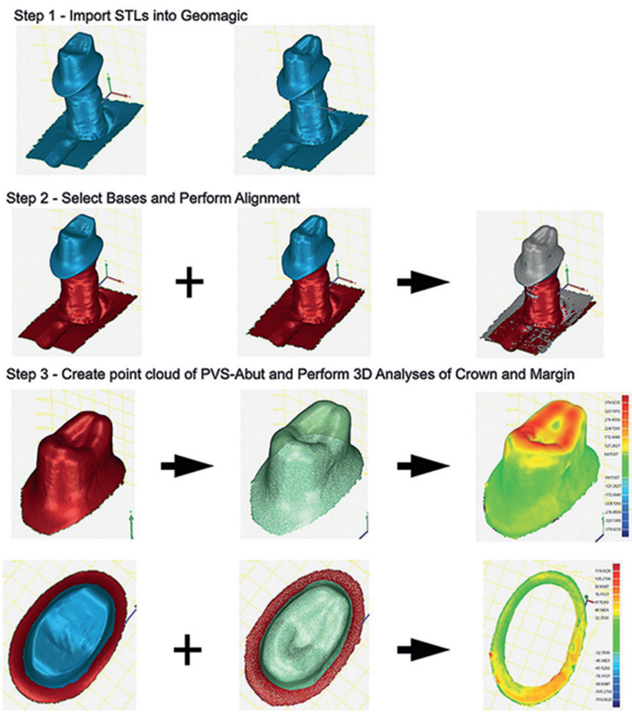

Figure 8. Geomagic alignment and measuring protocol. Step 1, STL files from Figures 7A and 7C imported into Geomagic software. Step 2, Bases and emergence portion of abutments highlighted and then first manually aligned at 3+ locations with "N-point alignment" function and then refined by using "best-fit alignment" function. Step 3, Once aligned, everything below finish line of abutment deleted. Abutment-PVS unit converted to point cloud. Software then used to measure entire internal fit and marginal discrepancy. PVS, polyvinyl siloxane; STL, standard tessellation language.

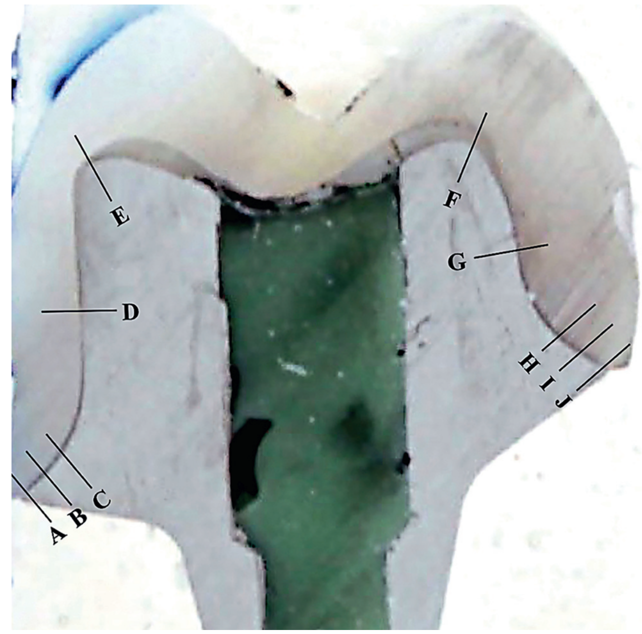

Figure 9. Sectioned specimen with measurement locations.

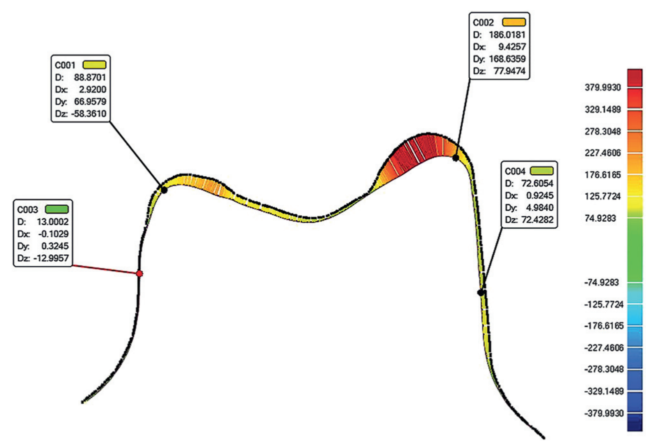

Figure 10. Geomagic cross section with measurement in micrometers.

adhered to the abutment. The PVS-coated abutment was then scanned using 3Shape D900.

Both the initial abutment scan and PVS-abutment scan were exported as STL files and imported into Geomagic software (Fig. 8, step 1). The bases were first aligned manually through N-point alignment, followed by the best-fit alignment function, checking high precision fitting and fine adjustments only to further correctly align the 2 scans (Fig. 8, step 2). The alignment was assessed with a 3D analysis of the selected aligned area. An alignment was considered successful if the deviation between the 2 scans was a positive average of 6 μm or less and a root mean square estimate was of 12 μm or less. These successful alignment values were determined from a pilot study.

Once the scans were successfully aligned, the bases and anything below the finishing line on the abutments of both scans were deleted, leaving only the abutment and the abutment-PVS unit of corresponding scans remaining. The abutment-PVS unit was then converted to a point cloud to increase the number of data points used for measuring. The entire PVS portion was highlighted and then converted to a point cloud of 200 000 points (Fig. 8, step 3).

Two major measurements were made using the Geomagic software. First, a 3D analysis was performed to assess the distance between the surface of the reference abutment and the point cloud of the abutment-PVS surface, thereby measuring the crowns' internal fit (Fig. 8, step 3). For each specimen, the average positive deviation of the internal fit was recorded. The deviation was averaged from nearly 197 000 data points. Second, the margins were highlighted on the reference abutment and PVS-abutment point cloud, and a 3D analysis was completed to assess the marginal gap (Fig. 8, step 3). Average positive deviation of the marginal gap was recorded. For

Table 1. Mean 2D scanning electron microscopy marginal opening of 3 experimental groups (μm)

Experimental Groups	N	Mean 2D SEM Marginal Opening ±SD	Group Comparisons (*P*)*	Maximum/Minimum/Median
Interrupted digital Atlantis (IDA)	7	13 ±9	FDSF (.002)	30/11/17
Full digital Atlantis (FDA)	7	11 ±3	FDSF (.002)	15/10/11
Full digital split-file (FDSF)	7	37 ±14	IDA (.002); FDA (.002)	58/35/47

SEM, scanning electron microscope; SD, standard deviation. *Group with which experimental group significantly different.

each marginal gap measurement, nearly 57 000 data points were used.

Once scans were completed for Geomagic measurements, abutments were then seated in a secure base, and their corresponding crowns were cemented (RelyX Luting Cement; 3M) using a standardized load of 22 N for 10 minutes. The specimens were embedded and then sectioned along the long axis in a buccal-lingual direction with a low-speed, water-cooled diamond sectioning saw (IsoMet Low Speed Saw; Buehler).

Ten measurements (Fig. 9) were made per specimen using a SEM (JEOL 6010LA; JEOL Inc). Marginal gap and marginal opening averages were used to evaluate the validation and repeatability of the measuring technique, and additional measurements were obtained. First, a 2D analysis was performed with the Geomagic software by creating a digital cross section through the 3D aligned abutment/abutment-PVS unit at approximately the same location as the buccal-lingual section of the corresponding SEM specimen. Two-dimensional Geomagic measurements were made at the same locations as the 2D SEM sectioned specimens. Using specimens from each group, a total of 50 measurements were recorded, 25 from 2D Geomagic and 25 of the same location of the same specimens from the 2D SEM (Fig. 10). The 50 measurements were used for statistical comparison. To ensure repeatability of the new Geomagic measuring technique, alignment and analysis were repeated on specimens from each group, totaling 8 different specimens. Results from first and second analyses were compared by statistical analysis.

Raw data were gathered from both Geomagic and SEM measurements, and statistical analyses were completed using statistical software (IBM SPSS Statistics, v19.0; IBM Corp) (α=.05). Kruskal-Wallis test (P<.05), followed by post hoc Mann-Whitney test, was performed with a Bonferroni correction of P<.017, adjusting for multiple comparisons. Measurements evaluated for group comparisons and statistical significance included SEM mean marginal opening, SEM mean marginal gap, Geomagic mean marginal gap, and Geomagic mean internal fit.

Statistical analyses were also used to evaluate validity and repeatability of the Geomagic measuring technique. Geomagic validation was demonstrated with 2 comparisons. First, the marginal gap averages of SEM and marginal gap averages of Geomagic were statistically compared for each group with a paired *t* test. Second, a total of 50 measurements, 25 two-dimensional SEM and 25 two-dimensional Geomagic measurements, were made at the same corresponding locations and statistically compared by a paired *t* test. Geomagic repeatability test results were statistically compared with those of a paired *t* test.

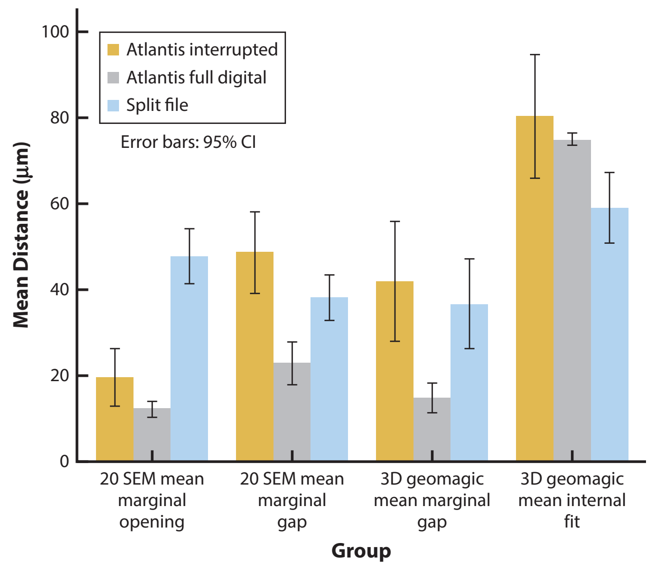

Figure 11. Mean values for 2D SEM and 3D Geomagic measurements. CI, confidence interval; SEM, scanning electron microscope.

RESULTS

The results of the Kruskal-Wallis and post hoc Mann-Whitney test for SEM marginal opening indicated that the 2 Atlantis workflows, IDA and FDA, were significantly smaller (P=.002) than the FDSF workflow (Table 1; Fig. 11). The results of the Kruskal-Wallis and post hoc Mann-Whitney tests for both SEM and Geomagic marginal gap averages indicated that the mean marginal gap for FDA workflow is significantly smaller than the average marginal gaps of the other 2 groups (SEM P=.002; Geomagic P=.004 for IDA and P=.006 for FDSF) (Tables 2, 3; Fig. 11). The results of the Kruskal-Wallis and post hoc Mann-Whitney test for Geomagic overall internal fit indicated that mean internal fit for the FDSF group was significantly smaller (P=.006) than that for the other 2 groups (Table 4; Fig. 11).

Table 2. Mean 2D scanning electron microscopy marginal gap of 3 experimental groups (µm)

Experimental Groups	N	Mean 2D SEM Marginal Opening ±SD	Group Comparisons (*P*)*	Maximum/Minimum/Median
Interrupted digital Atlantis (IDA)	7	48 ±10	FDA (.002)	63/36/45
Full digital Atlantis (FDA)	7	22 ±5	IDA (.002); FDSF (.002)	28/14/25
Full digital split-file (FDSF)	7	38 ±5	FDA (.002)	47/31/37

SEM, scanning electron microscope; SD, standard deviation. *Group with which experimental group significantly different.

Table 3. Mean 3D Geomagic marginal gap of 3 experimental groups (µm)

Experimental Groups	N	Mean 3D Geomagic Marginal Gap ±SD	Group Comparisons, (*P*)*	Maximum/Minimum/Median
Interrupted digital Atlantis (IDA)	6	41 ±13	FDA (.004)	58/23/41
Full digital Atlantis (FDA)	6	14 ±3	IDA (.004); FDSF (.006)	17/10/16
Full digital split-file (FDSF)	5	36 ±8	FDA (.006)	44/24/38

SD, standard deviation. *Group with which experimental group significantly different.

Table 4. Mean 3D Geomagic internal fit of 3 experimental groups (µm)

Experimental Groups	N	Mean 3D Geomagic Internal Fit ±SD	Group Comparisons (*P*)*	Maximum/Minimum/Median
Interrupted digital Atlantis (IDA)	6	80 ±13	FDSF (.006)	102/68/74
Full digital Atlantis (FDA)	6	74 ±1	FDSF (.006)	76/73/74
Full digital split-file (FDSF)	5	59 ±6	IDA (.006); FDA (.006)	65/48/61

SD, standard deviation. *Group with which experimental group significantly different.

The Geomagic measurement software was validated by 2 statistical analyses. The results of the paired *t* test for 25 two-dimensional SEM and 25 two-dimensional Geomagic sections made at the same location of specimens from all 3 groups indicated no statistical difference among measurements for all 3 groups (*P*=.101) (Fig. 11). Results of the paired *t* test used to compare the SEM mean marginal gap and Geomagic mean marginal gap indicated no statistically significant differences in measuring techniques (Table 5).

Geomagic repeatability was evaluated by comparing repeated marginal gap measurements taken from the same specimens. The results of the paired *t* test indicated no statistical difference among measurements for all 8 specimens (*P*=.490).

DISCUSSION

The accuracy of full digital workflows with digital design and milling of both a crown and custom abutment from a single STL file has been reported,[9] but the authors are unaware of previous studies assessing the internal fit and marginal gap of the 2 Atlantis digital workflows. Results from the present study indicate that all 3 workflows are clinically acceptable, as the average marginal gap assessed in each of the workflows was below the clinically acceptable 120-µm value (Fig. 12).

The split-file workflow showed the smallest internal fit compared with the Atlantis groups (Table 4). Upon evaluation of the internal fit, this could be due to the decreased occlusal cement space by way of the design of the split-file group, compared with the two Atlantis groups. Slight differences in settings or design could account for the variation in internal fit among the groups.

Table 5. Paired Student *t* test for comparison of 2D scanning electron microscopy mean marginal gap to 3D Geomagic mean marginal gap

Experimental Groups	N	*P*
Interrupted digital Atlantis	6	.221
Full digital Atlantis	6	.066*
Full digital split-file	5	.981

*Statistically significant (*P*<.05).

Sheridan et al[9] assessed the split-file workflow and reported, after adjustments, a mean marginal discrepancy of 69 µm. The present study found a smaller mean marginal opening and mean marginal gap ranging from 36 to 38 µm and, unlike the previous study, required no adjustments before seating.

The results of this study indicate that the full digital workflows tested can be used with reliability in practice, reducing the number of appointments, time, and cost. However, the Atlantis-interrupted digital workflow is also clinically acceptable, allowing clinicians to choose the most appropriate workflow for the clinical situation. In addition, this study validated and demonstrated statistically proven repeatability of the digital silicone replica technique using Geomagic software.

Limitations and sources of error of the study include the use of spray to reduce reflectivity before scanning the titanium abutments and a potential error associated with PVS material lifting away from the abutment surface, which may be imperceptible to the eye but could alter final measurements. Digital errors, such as errors from the scanner or alignment error associated with the Geomagic measuring technique, were also possible. As determined from a pilot study, the maximum allowable alignment error, and/or deviation, had a positive average of 6 µm or less and a root

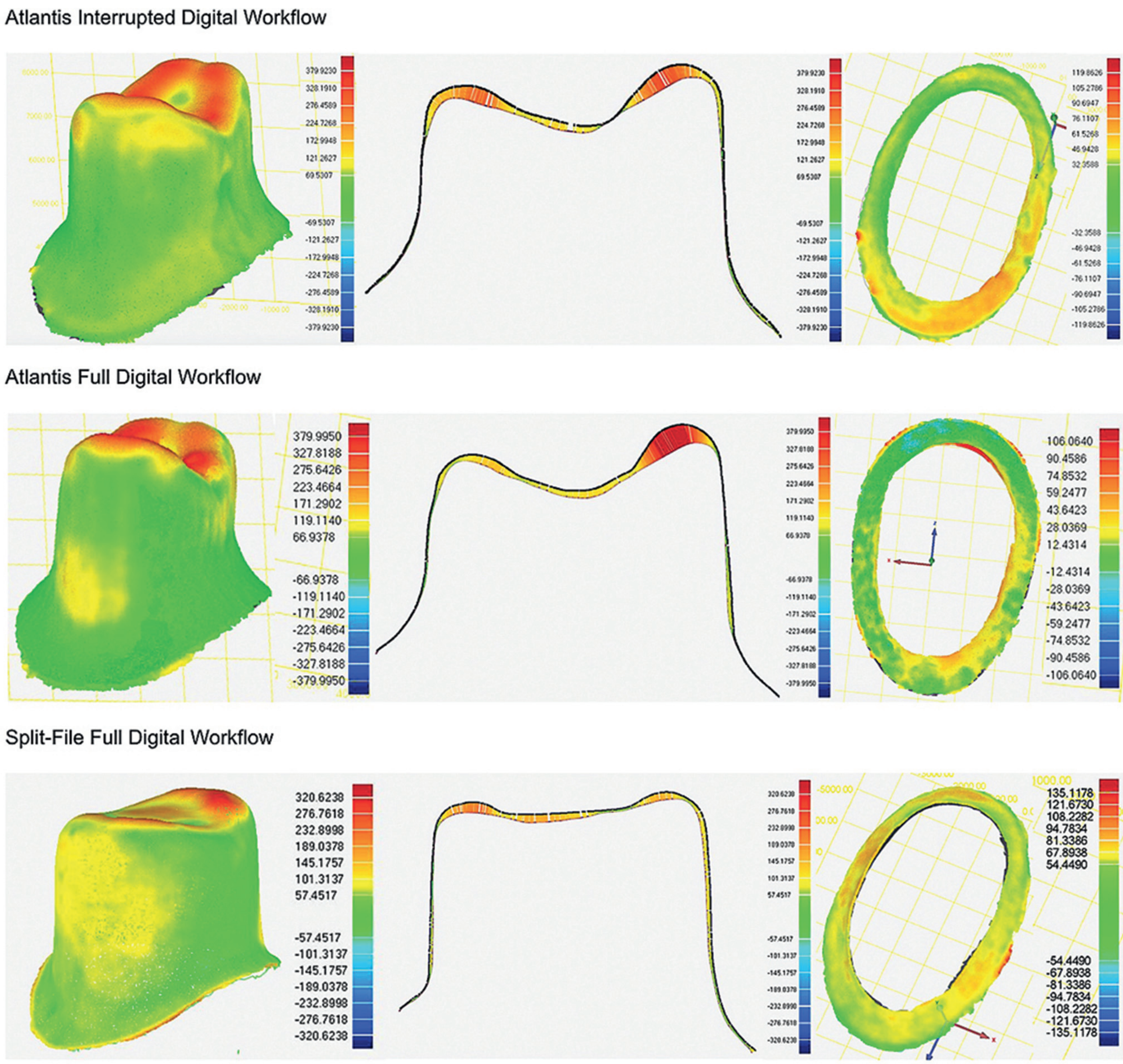

Figure 12. Geomagic 3D and 2D analysis of each group.

mean square estimate of 12 μm or less for each specimen analyzed. If any specimens had a greater error, they were realigned until a smaller deviation was obtained, or the specimen was eliminated from the data. Further studies are recommended to evaluate the wide array of digital workflows now available.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. All 3 workflows evaluated in this study show clinically acceptable results in terms of mean marginal gap below 120 μm.
2. The SEM evaluation of mean marginal opening revealed that the mean marginal opening of the IDA workflow and FDA workflow was statistically smaller than that of the FDSF workflow.
3. SEM and Geomagic measurements of the mean marginal gap revealed that the mean marginal gap of the FDA workflow was significantly smaller than that of the IDA workflow and FDSF workflow.
4. The Geomagic evaluation of the mean internal fit revealed that the mean internal fit of the FDSF workflow was significantly smaller than that of the IDA workflow and FDA workflow.

5. The use of Geomagic to measure and evaluate mean marginal gap and mean internal fit as defined in this study proved to be acceptable.

REFERENCES

1. Kapos T, Evans C. CAD-CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants 2014;29(Suppl):117-36.
2. Kim KB, Kim JH, Kim WC, Kim JH. Three-dimensional evaluation of gaps associated with fixed dental prostheses fabricated with new technologies. J Prosthet Dent 2014;112:1432-6.
3. Ng J, Ruse D, Wyatt C. A comparison of the marginal fit of crowns fabricated with digital and conventional methods. J Prosthet Dent 2014;112:555-60.
4. Brandt J, Lauer HC, Peter T, Brandt S. Digital process for an implant-supported fixed dental prosthesis: a clinical report. J Prosthet Dent 2015;114:469-73.
5. Joda T, Bragger U. Time-Efficiency analysis comparing digital and conventional workflows for implant crowns: a prospective clinical crossover trial. Int J Oral Maxillofac Implants 2015;30:1047-53.
6. Furze D, Byrne A, Donos N, Mardas N. Clinical and esthetic outcomes of single-tooth implants in the anterior maxilla. Quintessence Int 2012;43:127-34.
7. Ferrari M, Tricarico MG, Cagidiaco MC, Vichi A, Gherlone EF, Zarone F, et al. 3-Year Randomized controlled prospective clinical trial on different CAD-CAM implant abutments. Clin Implant Dent Relat Res 2016;18:1134-41.
8. Gehrke P, Johannson D, Fischer C, Stawarczyk B, Beuer F. In vitro fatigue and fracture resistance of one- and two-piece CAD-CAM zirconia implant abutments. Int J Oral Maxillofac Implants 2015;30:546-54.
9. Sheridan RR, Haney S, Haney S, Schoolfield J. Effect of split-file digital workflow on crown margin adaptation. J Prosthodont 2017;26:571-80.
10. Christensen GJ. Marginal fit of gold inlay castings. J Prosthet Dent 1966;16:297-305.
11. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. Br Dent J 1971;131:107-11.
12. Martinez-Rus F, Ferreiroa A, Ozcan M, Pradies G. Marginal discrepancy of monolithic and veneered all-ceramic crowns on titanium and zirconia implant abutments before and after adhesive cementation: a scanning electron microscopy analysis. Int J Oral Maxillofac Implants 2013;28:480-7.
13. Groten M, Axmann D, Probster L, Weber H. Determination of the minimum number of marginal gap measurements required for practical in-vitro testing. J Prosthet Dent 2000;83:40-9.
14. Holst S, Karl M, Wichmann M, Matta RE. A new triple-scan protocol for 3D fit assessment of dental restorations. Quintessence Int 2011;42:651-7.
15. Holst S, Karl M, Wichmann M, Matta RE. A technique for in vitro fit assessment of multi-unit screw-retained implant restorations: application of a triple-scan protocol. J Dent Biomech 2012;3:1758736012452181.
16. Luthardt RG, Kuhmstedt P, Walter MH. A new method for the computer-aided evaluation of three-dimensional changes in gypsum materials. Dent Mater 2003;19:19-24.
17. Luthardt RG, Bornemann G, Lemelson S, Walter MH, Huls A. An innovative method for evaluation of the 3-D internal fit of CAD-CAM crowns fabricated after direct optical versus indirect laser scan digitizing. Int J Prosthodont 2004;17:680-5.
18. Luthardt RG, Loos R, Quaas S. Accuracy of intraoral data acquisition in comparison to the conventional impression. Int J Comput Dent 2005;8:283-94.
19. Moldovan O, Luthardt RG, Corcodel N, Rudolph H. Three-dimensional fit of CAD-CAM-made zirconia copings. Dent Mater 2011;27:1273-8.
20. Anadioti E, Aquilino SA, Gratton DG, Holloway JA, Denry I, Thomas GW, et al. 3D and 2D marginal fit of pressed and CAD-CAM lithium disilicate crowns made from digital and conventional impressions. J Prosthodont 2014;23:610-7.
21. Alfaro DP, Ruse ND, Carvalho RM, Wyatt CC. Assessment of the internal fit of lithium disilicate crowns using micro-CT. J Prosthodont 2015;24:381-6.
22. Lee DH. Digital approach to assessing the 3-dimensional misfit of fixed dental prostheses. J Prosthet Dent 2016;116:836-9.
23. Ortega R, Gonzalo E, Gomez-Polo M, Suarez MJ. Marginal and internal discrepancies of posterior zirconia-based crowns fabricated with three different CAD-CAM systems versus metal-ceramic. Int J Prosthodont 2015;28:509-11.
24. Apicella D, Veltri M, Chieffi N, Balleri P, Ferrari M. Cement thickness at implant-supported single-tooth Lava assemblies: a scanning electron microscopic investigation. Clin Oral Implants Res 2010;21:747-50.

Corresponding author:
Dr Stephanie Zeller
Private practice
Seattle, WA.
Email: StephanieKZeller@gmail.com

Acknowledgments
The authors thank Maury Alvarez from Providence Prosthodontics Dental Group for his time, dedication, and assistance in this project. The authors also thank Ryan Sheridan for advice, guidance, and information regarding this project. They also thank Evan Kemper from Whip Mix Corp for his assistance with the 3Shape software. In addition, authors thank Alireza Tavassoli from Biodenta for parts and design assistance and with this project. The authors would also like to thank Dr Stephan Holst and Dr Ragai Matta for their communication on the Triple Scan Protocol and also Dr Eva Anadioti for communication regarding her published measuring protocol.

https://doi.org/10.1016/j.prosdent.2018.04.026