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ORIGINAL ARTICLE

Complete digital workflow for prosthesis prototype fabrication with double digital scanning: A retrospective study with 45 edentulous jaws

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Abstract

Purpose: To assess the accuracy of fit of complete-arch printed prosthesis prototypes generated with a digital workflow protocol for completely edentulous jaws.

Materials and methods: Forty-five edentulous jaws (35 patients) underwent intraoral complete-arch digital scans with the double digital scanning (DDS) technique and the generated standard tessellation language (STL) files were superimposed and imported into computer-aided design software. After STL merging, each master STL file was used for printing a prosthesis prototype. The primary outcome was the accuracy of fit assessment of the printed prototypes on verified master stone casts. Two experienced clinicians tested the accuracy of fit with radiographs and screw-resistance tests. Secondary outcomes were the effect of the scan body shape and implant number on the accuracy of fit.

Results: Out of the 45 DDS-generated prosthesis prototypes, 39 presented with accurate fit on verified master stone casts, yielding an 86.70% accuracy of fit. Cylindrical scan bodies led to 100% accuracy of fit (25/25), whereas polygonal scan bodies presented with 70% accuracy of fit (14/20). Four implant-supported prostheses yielded 100% accuracy of fit (12/12), compared with 25/29 (86.30%) accuracy of fit for the six-implant-supported ones. Fisher's exact test was used to assess the effect of different scan body shapes ($p = 0.005$) and implant number on accuracy of fit. Chi-squared test was used to assess the association between the number of implants per arch and the accuracy of fit ($p = 0.039$).

Conclusions: Thirty-nine out of 45 complete-arch prosthesis prototypes generated with a completely digital workflow presented with clinically acceptable fit. The effect of the scan body design and implant number was statistically significant, favoring cylindrical scan bodies and four-implant-supported prostheses.

KEYWORDS
3D printing, complete digital workflow, complete-arch digital scan, complete-arch implant rehabilitation, dental implants, digital implant impression, digital implant scan, digital workflow, full-arch digital scan, full-arch prosthesis, full-arch zirconia, implant rehabilitation

Complete-arch digital implant scanning for completely edentulous jaws is a scientifically and clinically validated procedure.[1–6] After successful implant osseointegration, the restorative phase commences with the double digital scanning (DDS) of the implant scan bodies and the screw-retained interim prosthesis for data acquisition and virtual articulation in a single appointment.[5–12] The standard tessellation language (STL) files from the two scans are merged and imported into computer-aided design (CAD) software for further design and printing/milling of the prosthesis prototype.[5–8] The prosthesis prototype serves as the blueprint for the definitive implant-supported fixed complete dental prosthesis (IFCDP) and its accuracy of fit is incumbent for treatment success.[13–18]

It has been reported that the STL files derived from intraoral scanning demonstrate comparable accuracy to the splinted open-tray impression technique.[1–3] A recent systematic review reported that complete-arch digital scans had comparable accuracy with conventional impressions.[4] The issue that arises is data merging and articulation of the STL files that are generated from the DDS technique, mainly due to the absence of anatomical landmarks such as teeth.[5–12] Recent clinical reports have demonstrated protocols for the fabrication of digitally manufactured prosthesis prototypes utilizing fiducial markers for the STL data merging with the DDS technique.[1–8]

The purpose of this retrospective study was to assess the accuracy of fit of printed prosthesis prototypes using a complete digital workflow protocol for 45 completely edentulous maxillae and mandibles. The primary outcome measure was the assessment of the accuracy of fit of the digitally fabricated prosthesis prototypes on verified master casts. Secondary outcomes were the effect of the scan body shape and implant number on the accuracy of fit.

MATERIALS AND METHODS

The present retrospective study was performed at the Department of Prosthodontics at Tufts University School of Dental Medicine (TUSDM). The Tufts Health Sciences Institutional Review Board (IRB) committee at TUSDM approved the study (IRB #2183). Completely edentulous patients, with at least one edentulous jaw, who had been treated with one-piece, screw-retained zirconia IFCDPs, supported by 245 implants (Straumann, Switzerland; Nobel Biocare, Sweden) between January 2019 and November 2021 were eligible for inclusion in the study. These patients were identified through the Axium files and de-identified stone casts that had been kept in the laboratory of the prosthodontics clinic.

The prosthetic rehabilitation procedures have been previously published.[1] After a successful implant osseointegration period of 3 months, each patient underwent conventional abutment-level complete-arch impression after connecting abutment-level impression copings (Impression post for SRA open-tray, Institute Straumann AG, Switzerland) to the implant abutments (Straumann SRA abutments, Institute Straumann AG, Switzerland). All copings were splinted together using prefabricated bars made from urethane dimethacrylate–based visible light-cured resin (Triad gel; Dentsply Inc, York, PA). The resin bars were luted to the impression copings with a minimal amount of the material. Complete-arch impressions were then taken using polyether material (Impregum; 3M ESPE, St. Paul, MN). The generated impressions were poured with low type IV expansion stone (Resin Rock, Whip Mix Corp, Louisville, KY) to fabricate conventional stone casts. All stone casts were successfully verified with the fabrication of intraoral verification jigs and served as a reference.[1,2,12]

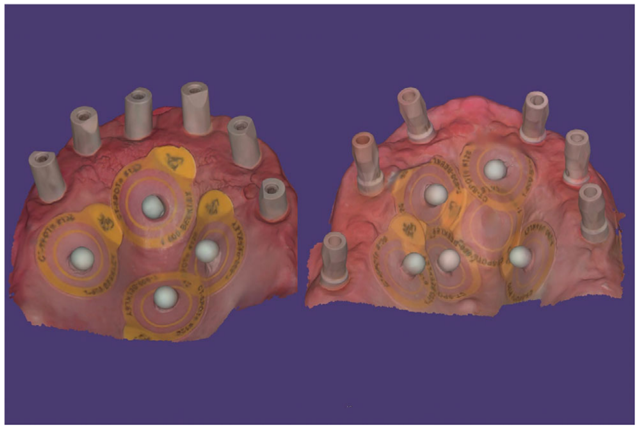

FIGURE 1 Cylindrical versus polygonal scan bodies

Subsequently, each patient underwent complete-arch digital scans with a confocal microscopy intraoral scanner (TRIOS 3, 3Shape A/S, Copenhagen, Denmark) and the DDS technique.[1–5] Scan path was standardized, starting from occlusal continuing to palatal/lingual and finishing at the buccal area. Scan bodies from three different manufacturers (CARES Mono Scan body for screw-retained abutment, Straumann; ELOS multiunit scan body, ELOS Medtech; GM Mini Conical Abutment Scan Body, Neodent) were used according to the implant system and hand tightened, according to the manufacturer recommendation. Cylindrical SRA scan bodies (SRA Scanbody, Institute Straumann AG, Switzerland) were used for the Straumann system.[1] For the Nobel Biocare system, due to the interchangeability of the parts, ELOS multiunit scan body (ELOS Medtech) (cylindrical shape) and Mini Conical Abutment scan body (Neodent) (polygonal shape) scan bodies were used (Fig 1).

For the maxillary jaws, four to six sphere-shaped self-adhesive fiducial markers (CT-SPOT 120, Beekley Medical, Bristol, CT) were glued over the keratinized gingiva of the palate prior to DDS to aid in STL data merging.[1–5] An initial complete-arch digital scan that included the interim prosthesis and the fiducial markers was taken, followed by a second complete-arch digital scan of the implant scan bodies (Fig 2). For the mandibular jaws, the same clinical procedures were carried out, and fiducial markers were used for STL data merging (either surgical anchor pins, or fiducial markers and pins).[8,12] One experienced clinician (PP) supervised all the

FIGURE 2 Double digital scanning (DDS) of scan bodies and interim prosthesis leading to standard tessellation language (STL) merging for fabrication of printed prosthesis prototype

FIGURE 4 Double digital scanning (DDS)-generated prosthesis prototype seated on verified cast, indicating accurate fit

FIGURE 3 Printed prosthesis prototype prior to freehand cementation of the titanium inserts in the respective positions

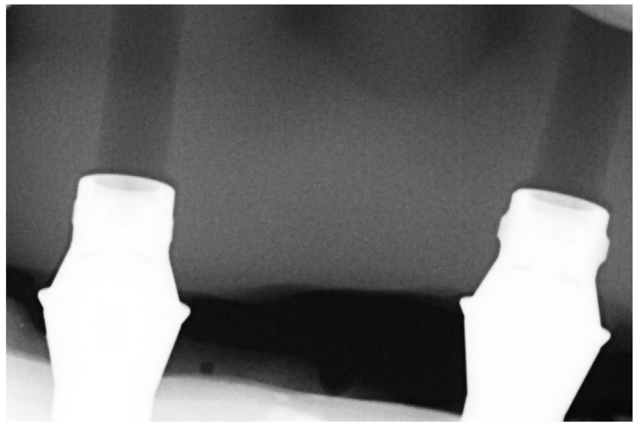

FIGURE 5 Periapical radiograph indicating accurate fit

digital scans. Both STL files from each scanned jaw were imported in a dedicated CAD software (Exocad DentalCAD, exocad GmbH, Darmstadt, Germany), and merging of the files was performed by an experienced laboratory technician (YK) using the fiducial markers.[4–8]

The master STL file that was generated after merging of STL files from DDS of scan bodies and interim prostheses was imported into a three-dimensional (3D) printer (M2 Carbon 3D CLIP printer, Carbon, Redwood City, CA) to design and produce a prototype prosthesis. Titanium inserts (Variobase for Bridge/Bar, Institute Straumann AG, Switzerland; Accurate Hybrid Base, ELOS; Neo Mini Conical Abutment, Neodent) were freehand cemented to each prototype using cyanoacrylate cement (Fig 3).[8]

Two experienced clinicians (PP, KV) evaluated the accuracy of fit of each printed prosthesis prototype over the respective verified master cast using visual, radiographic, and screw-resistance test.[8,13–15] First, each prosthesis was placed over the abutment analogs to visually inspect for macroscopic gaps at the interfaces between the analogs and the titanium bases under 2.5× magnification loupes (SurgiTel Pro Line; SurgiTel, Ann Arbor, MI). Then, the prosthesis prototype was tightened, and the clinicians assessed the overall screw resistance during tightening.[8,13–15] Periapical radiographs were taken for every abutment–prosthesis interface with the parallel cone technique (Fig 4 and 5). Any visual or radiographic presence of gap between abutment and platform after tightening all the screws was considered misfit (Fig 6 and 7). The decision was made to assess the fit of the prototype prosthesis on verified master casts and not in the mouth to visually inspect the abutment platform interface.

After fit assessment on the verified stone casts, the prosthesis prototypes were tried in intraorally and after esthetic and functional adjustments were finalized, they were digitally rescanned and copy-milled into zirconia definitive prostheses. At the definitive prosthesis insertion appointment, all 45 jaws received an accurately fitting zirconia IFCDP (Fig 8).

FIGURE 6 Double digital scanning (DDS)-generated prosthesis prototype seated on verified cast, indicating misfit

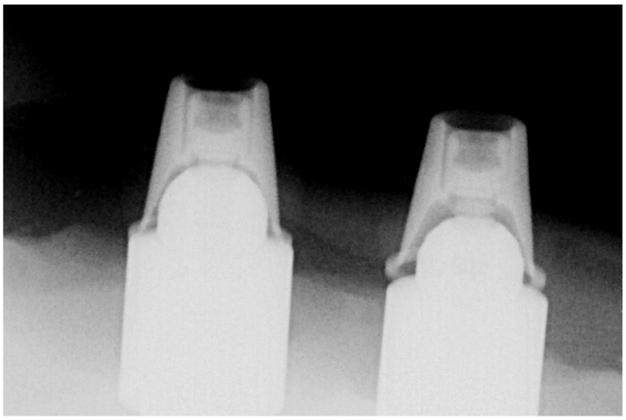

FIGURE 7 Periapical radiograph indicating misfit

STATISTICAL ANALYSIS

Descriptive statistics (frequencies and percentages) were calculated for the outcome variable (the fit assessment [fit vs. misfit], implant system [Straumann vs. Nobel Biocare], arch [maxillary vs. mandibular], number of implants per arch (four, five, or six implants), and the shape of scan bodies [cylindrical vs. polygonal]). The Chi-squared test was used to assess the association between the number of implants per arch and accuracy of fit. Fisher's exact test was used to assess the association between the shape of the scan bodies and accuracy of fit. The *p*-value cutoff was set as 0.05. The IBM SPSS software version 27.0 was used in all the statistical analyses.

RESULTS

A total of 45 edentulous jaws (35 patients) were treated with screw-retained, zirconia IFCDPs. Twelve jaws (12 patients) received 4 implants, 4 jaws (4 patients) received 5 implants, and 29 jaws (19 patients) received 6 implants (Table 1). Of the 45 edentulous jaws, 20 jaws (44.40%) had received Straumann versus 25 jaws (55.60%) that received Nobel Biocare implants. Twenty-six jaws (57.80%) were maxillary versus 19 (42.20%) mandibular. Regarding the technique for merging the STL files, 21 prototypes (46.6%) were designed based on the fiducial markers merging technique, whereas 24 (53.47%) were based on fiducial markers and surgical anchor pins. Cylindrical scan bodies (SRA Mono scan body; ELOS multiunit scan body) were used in the digital workflow to design 25 prototype prostheses (55.60%), whereas the polygonal scan bodies (GM Mini Conical Abutment scan body) were used in the remaining 20 prototype workflows.

TABLE 1 Descriptive statistics for the 45 edentulous jaws

	Frequencies	%
Implant brand		
Straumann	20	44.40
Nobel	25	55.60
Arch		
Maxilla	26	57.80
Mandible	19	42.20
Number of implants per IFCDP		
Four Implants	12	26.70
Five Implants	4	8.90
Six Implants	29	64.40
Scan body shape		
Cylindrical	25	55.60
Polygonal	20	44.40
Accuracy of fit assessment		
Fit	39	86.70
Misfit	6	13.30

Abbreviation: IFCDP, implant-supported fixed complete dental prosthesis.

The subjective assessment of fit of the complete-arch printed prototype prostheses over the verified master casts yielded outcomes shown in Table 2. Out of the 45 DDS-generated prototype prostheses, 39 presented with accurate fit on verified master stone casts, yielding a cumulative 86.70% accuracy of fit. When data were broken down based on scan body shape, cylindrical scan bodies led to 100% accuracy of fit (25/25), whereas polygonal scan bodies presented with 70% accuracy of fit (14/20). Fisher's exact test revealed a statistically significant difference in the accuracy of fit of the prototypes between the cylindrical and polygonal shape of scan bodies (p-value = 0.005). Regarding the number of implants used per jaw, the Chi-squared test revelated a significant difference in the accuracy of the fit of the prototypes ($p = 0.039$). When four implants were used per jaw to support the IFCDPs, 100% (12/12) accuracy of fit was achieved compared to 50% (2/4) accuracy of fit when using five implants, and 86.30% (25/29) accuracy of fit for the six implants. Regarding the edentulous jaw, maxillary and mandibular jaws were significantly different in terms

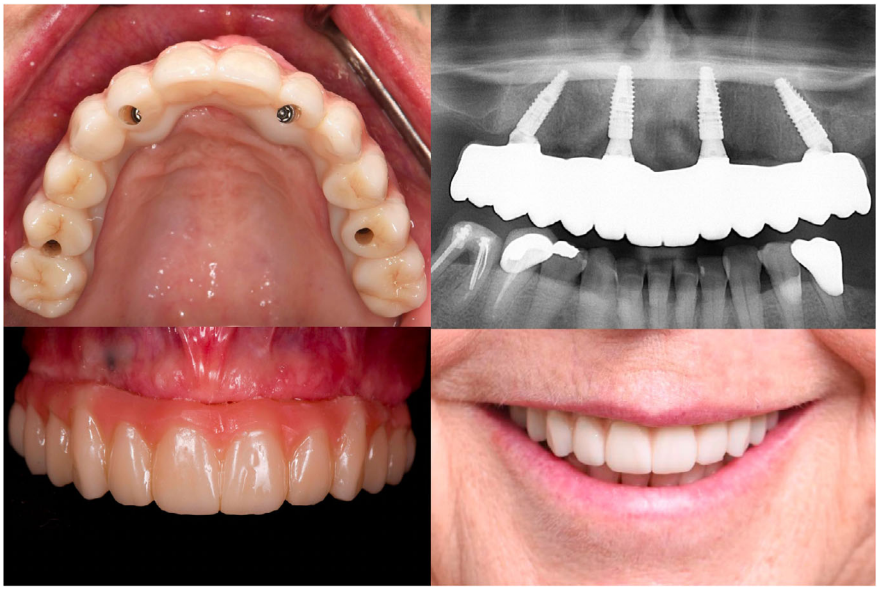

FIGURE 8 Definitive maxillary zirconia implant-supported fixed complete dental prosthesis (IFCDP) fabricated with a complete digital workflow

TABLE 2 The assessment of fit association with the study variables

	Fit		Misfit		
	Frequencies	**%**	**Frequencies**	**%**	***p*-Value**
Scan body shape					
Cylindrical (*n* = 25 jaws)	25	100.00	0	0.00	0.005*
Polygonal (*n* = 20 jaws)	14	70.00	6	30.00	
Arch					
Maxilla (*n* = 26)	20	76.92	6	23.08	0.028*
Mandible (*n* = 19)	19	100.00	0	0.00	
Number of implants per IFCDP					0.039*
Four Implants (*n* = 12)	12	100.00	0	0.00	
Five implants (*n* = 4)	2	50.00	2	50.00	
Six implants (*n* = 29)	25	86.20	4	13.80	

Abbreviation: IFCDP, implant-supported fixed complete dental prosthesis.
*statistical significance.

of the assessment of the fit. Out of the 45 prototypes, 20/26 (76.90%) of the maxillary prototypes fitted compared to 19/19 (100%) of the mandibular prototypes ($p = 0.028$).

DISCUSSION

The purpose of this retrospective study was to assess the accuracy of fit of printed prosthesis prototypes using a digital workflow protocol for 45 completely edentulous maxillae and mandibles. The primary outcome measure was the assessment of accuracy of fit of the digitally fabricated prosthesis prototypes on verified master casts. Secondary outcomes were the effect of the scan body shape and implant number on the accuracy of fit.

The findings of this clinical study showed that 39 out of the 45 digitally fabricated prototypes from the DDS technique presented with accurate fit under assessment on verified master stone casts by two experienced prosthodontists, yielding an 86.70% accuracy of fit. Cylindrical scan bodies led to 100% accuracy of fit (25/25), whereas polygonal scan bodies presented with 70% accuracy of fit (14/20). This is the first clinical study reporting outcomes with different scan body shapes, indicating that the data acquisition and subsequent merging with cylindrical scan bodies were significantly more accurate than the outcomes with polygonal ones. Previous in vitro research has indicated that the scan body shape effects accuracy, but recommendations on shape design have been inconclusive.[16–22] It has been reported that shorter scan bodies with fewer undercuts may be easier to scan, process, and digitize. In this context, cylindrical scan bodies may provide a more advantageous geometry compared with the polygonal ones. Clinical implications from these findings are that digitally fabricated prosthesis prototypes can be generated with a complete digital workflow leading to clinically acceptable fit when using cylindrical scan bodies. Regarding the scan body, besides the shape, other variables can also affect the accuracy of the intraoral scanning, such as the material and surface finish (smooth vs. matte), its size, and its connection type (metal vs. plastic).

It must be mentioned that during the cascade of data acquisition with intraoral scanning, merging of the generated STL files, CAD design, and 3D printing, there may be an accumulation of errors that can be impossible to quantify and measure. Additionally, the implant angulation and depth, the operator experience, the inter-implant distance, and the type of intraoral scanner, as well as ambient environmental conditions, affect the accuracy of complete-arch digital scans. The effect of the M2 Carbon 3D CLIP printer (Carbon, Redwood City, CA) could also be one of the variables causing the misfit due to dimensional inaccuracies of the printed prototypes. However, in the present study, and for the six prototypes that presented with misfit, the same prototype was reprinted three times, and then the assessment of fit was repeated. For all three attempts for all six prototypes, the result was misfit. One additional step was done, attempting to eliminate the effect of the printer, by further reprinting with another 3D printer (Form 3b+; Formlabs Inc, Somerville, MA), and the result was again misfit. The printer properties could have been another variable affecting the accuracy. In the present study, 3D printers with continuous liquid interface production (Carbon M2) and stereolithography technology (Form 3b+) were used for the re-printing of the 6 non-fitting prosthesis prototypes.

Regarding the number of implants used per jaw and the effect on the accuracy of fit, it was found that when four implants were used per jaw to support the IFCDPs, 12/12 (100%) accuracy of fit was achieved compared to 2/4 (50%) accuracy of fit when using five implants, and 25/29 (86.30%) accuracy of fit for the six implants. The sample size comparing 12 four-implant impressions versus 29 six-implant impressions was limited, making definitive conclusions impossible. A previous clinical study by Chochlidakis et al reported less 3D implant deviations with four- versus six-implant impressions (digital vs. conventional).[2] Another systematic review indicated that the implant number may influence the accuracy of the digital complete-arch scan.[16] It can be only hypothesized that fewer implants led to more accurate data acquisition due to less accumulated errors with image stitching.

Regarding the edentulous jaw, maxillary and mandibular jaws were significantly different in terms of the assessment of the fit. Out of the 45 prototypes, 20/26 (76.90%) of the maxillary prototypes fitted compared to 19/19 (100%) mandibular prototypes (p =0.028). This is contradictory to what has been published in the in vitro literature, indicating nominally more 3D implant deviations with mandibular versus maxillary scans, but not statistically significant.[1] In the present study, all six jaws that presented with non-fitting prototypes were in the maxilla, and polygonal scan bodies had been used. It can be hypothesized that the polygonal scan bodies led to inaccurate data acquisition.

Regarding the cementation of the titanium inserts (bases) in the prototypes, this was performed without a cast, and cyanoacrylate cement was used to secure them with a free-hand approach, as described in a previous clinical study.[8] The titanium inserts fit precisely with either vertical stop and four lateral camshafts (Straumann) minimizing rotational freedom or vertical stop and cylindrical design (Neodent) for snap fit. The impact of the cement remains unknown.

Advantages of the present study include the clinical implementation from DDS to prosthesis prototype fabrication for the first time for both maxillae and mandibles, indicating a high percentage of fit. The clinical value of this article is highlighted by the reduction in the number of clinical appointments required by skipping the maxillomandibular relationship appointment.[1–8] During the DDS appointment, it is advisable to generate a verification jig. This can be easily done with different approaches such as intraoral splinting of copings and then tightening analogs prior to pouring a jig cast or similarly back-pouring the conversion prosthesis. A digital alternative to verification is using the STL data from digital full-arch scan to fabricate a digitally designed milled or printed verification jig through a complete digital workflow.[23] The verification jig cast will serve as quality control during the complete digital workflow, aid in the cementation of the titanium inserts for both prototype and definitive prostheses on the jig cast, and ultimately ensure acceptable fit. The accuracy of fit of the generated prosthesis prototype and definitive prosthesis is crucial for long-term success as it has been shown that complications with IFCDPs are frequent and time-dependent even when all prosthodontic procedures are done per strict protocol.[24–28]

One limitation of the present clinical study includes the limited sample size, which was a convenience sample. It was originally planned to investigate the accuracy of fit of DDS-generated prototype prostheses on this cohort of patients. When breaking down the data, the effect of the scan body was identified, but it was revealed that there was a difference in the groups (20 polygonal shape versus 25 cylindrical shape). Upon consultation with the statistician, he suggested moving forward even though there was a difference in the number of subjects per group. For this reason, further clinical studies are needed with larger sample sizes to corroborate the findings of the present study. Another limitation of this study was the subjective nature of assessment of the accuracy of fit by two experienced prosthodontists. However, all 45 edentulous jaws were restored with accurately fitting monolithic zirconia IFCDPs. Future research should focus on the clinical implementation of this digital protocol in the world of private practice. Finally, the effect of the implant angulation, printer properties and inter-implant distance, and implant number on the accuracy of fit warrants further investigation with larger patient cohorts.

CONCLUSIONS

Within the limitations of this clinical study, a few conclusions can be drawn. Thirty-nine out of 45 complete-arch prosthesis prototypes were generated with a complete digital workflow presented with clinically acceptable fit. The effect of the scan body design and implant number was statistically significant, favoring cylindrical scan bodies and four-implant-supported prostheses.

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CONFLICT OF INTEREST

The authors do not have any financial interest in the companies, the materials of which are included in this article.

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