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CLINICAL RESEARCH

Accuracy of cone beam computed tomography–derived casts: A comparative study

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ABSTRACT

Statement of problem. The accuracy of the external surface and internal trabecular architecture of large cone beam computed tomography (CBCT)–derived dentomaxillofacial anatomic casts has not yet been thoroughly investigated.

Purpose. The purpose of this comparative study was to evaluate the quantitative accuracy of CBCT-derived mandibular casts by applying an innovative land-mark free methodology.

Material and methods. Following inclusion and exclusion criteria, a CBCT scan of an 18-year-old woman was acquired. The mandible was segmented and isolated from the data set. The segmented mandible included depiction of the cortical surface, trabecular architecture, erupted teeth, and impacted third molars with incomplete root formation. Fifteen mandibular casts were fabricated by using multijet (MJ=4), digital light processing (DLP=4), stereolithography (SLA=2), fused deposition modeling (FDM=2), colorjet (CJ=2), and selective laser sintering (LS=1)-based high-quality medical commercial and office printers. Each printed cast was scanned and superimposed onto the original mandible, and the accuracy of the complete mandible and individual surfaces were assessed with a color-coded map.

Results. When the overall combined error associated with complete casts based on printing technology were compared, MJ showed the highest accuracy (0.6 ±0.7 mm). FDM technology (2.2 ±3.4 mm) had the highest overall absolute mean difference. No significant difference was observed when both individual surfaces and the complete mandible were compared.

Conclusions. Overall, casts replicated the skeletal and dental anatomic surfaces well. However, shortcomings were observed in relation to depicting trabecular architecture. (J Prosthet Dent 2020;■:■-■)

Recent advances in 3D printing, also known as additive rapid prototyping, and modeling has revolutionized medicine and dentistry.[1] Three-dimensional printing together with digital imaging including intraoral scanning, cone beam computed tomography (CBCT), and magnetic resonance imaging has been used for fabricating 3D printed casts or biomodels,[2] a generic term for biomedical prototypes defined as the replication of anatomic structures into a 3D physical model.[3] A benefit of such casts is the interaction with the patient's anatomy that adds information for diagnosis, treatment planning, and clinical training.[4-6] The introduction of such biomodels and virtual planning has improved the communication between radiologists and surgeons.[7,8]

Additive manufacturing and rapid prototyping technologies and processes have been used for making such casts with multiple layer by layer deposition of printing

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Clinical Implications

Clinicians should be careful when selecting printing technology and material for manufacturing dentomaxillofacial structures, as this may influence the diagnosis, treatment planning, and simulation of a prosthodontic procedure.

material, which stack up to form the 3D object.[9] These include stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), selective laser melting, polyjet (PJ), and electronic beam melting.[3,9,10] In addition to the technology-based classification of 3D printers, the process of printing can be classified as liquid-based, solid-based, or powder-based materials.[11]

Studies evaluating the surface accuracy of 3D-printed skeletal casts with accurate representation of anatomic structures are sparse. Most of the studies assessing the accuracy of such casts used landmarks with intraobserver and interobserver error.[12-15] The authors are unaware of studies on the accuracy of the surfaces using the internal trabecular architecture of large CBCT-derived dentomaxillofacial anatomic casts. Therefore, the current study was conducted to evaluate the quantitative accuracy of CBCT-derived mandibular casts by applying an innovative landmark-free methodology. The null hypothesis was that no significant differences would be found related to the accuracy of different casts.

MATERIAL AND METHODS

This research was carried out in compliance with the World Medical Association Declaration of Helsinki on medical research. The study was approved by the Ethical Review Board of the University Hospitals Leuven, Belgium (reference number: S57587) for collecting and using patient imaging data. Informed consent was not required as patient-specific information was anonymized.

A CBCT scan was acquired of an 18-year-old woman referred to the Department of Restorative Dentistry for evaluation of traumatized maxillary central incisors. Scanning was performed with a CBCT device (Newtom VGi evo; NewTom Inc), operating at 110 kV with a slice thickness of 0.15 mm and 11×10 cm field of view. Inclusion criteria involved a good quality image, presence of the entire mandible, normal cortical bone, dense trabecular architecture, and impacted mandibular third molars with incomplete root formation. The exclusion criteria were the presence of any pathological condition, restorations, and artifacts in the mandibular region. The image was exported in Digital Imaging and Communications in Medicine (DICOM) format for further processing.

The DICOM data were imported to 3D-segmentation software (Mimics inPrint; Materialise), where a combination of automatic and manual thresholding was applied to segment and isolate the mandible from the CBCT volume. A cutting plane was applied at the inferior border of the mandible to expose the trabecular architecture and at the posterior border to expose the roots of the impacted third molars (Fig. 1). The segmented anatomic structures in the definitive standard tessellation language (STL) file of the mandible depicted the cortical surface, trabecular architecture, erupted teeth, and impacted third molars with incomplete root formation.

Fifteen mandibular casts were fabricated from the original STL by using multijet (MJ=4), digital light processing (DLP=4), stereolithography (SLA=2), fused deposition modeling (FDM=2), colorjet (CJ=2), and selective laser sintering (LS=1) based high-quality medical commercial and in-office printers. A combination of various printers, materials, and layer resolutions were used to generate anatomic replicas of the mandible (Table 1).

After postprocessing, each cast was scanned with the Newtom VGi-evo CBCT device (high resolution, kV=110, slice thickness=0.125 mm, field of view = 10×5 cm) (Fig. 2) and segmented following the same protocol as that for the original mandibular STL by applying thresholding to create an STL file for each cast.

Each printed cast from the STL file was superimposed onto the original DICOM file of the mandible by applying a rigid voxel-based registration algorithm with mutual information[16] in an image processing software (Amira; FEI). This superimposition oriented the printed cast in the same 3D coordinates as those of the original STL file for accurate comparison of the anatomic structures (Fig. 3). The transformed position of the STL file after superimposition was then exported.

Both the original and transformed printed casts from the STL files were imported to 3D modeling software (3-matic; Materialise) for surface extraction and comparison. Both the original and printed mandibular cast STL files were divided into 6 separate anatomic regions (buccal and lingual surface, trabecular surface, erupted teeth, and impacted left and right third molars) to evaluate the printing accuracy of each surface individually (Fig. 4).

Both the complete mandible and extracted surfaces (buccal, lingual, trabecular, erupted teeth, impacted third molars) of the 3D printed cast were superimposed with those of the original CBCT-derived reference STL file individually. A part comparison with a color-coded map was carried out to evaluate the absolute mean difference (mm) between the complete mandible and each surface of the printed and original STL file (Fig. 5).

Two observers (S.S., F.N.) performed the assessment twice blindly and repeated the observations at an interval of 2 weeks to calculate the interobserver and

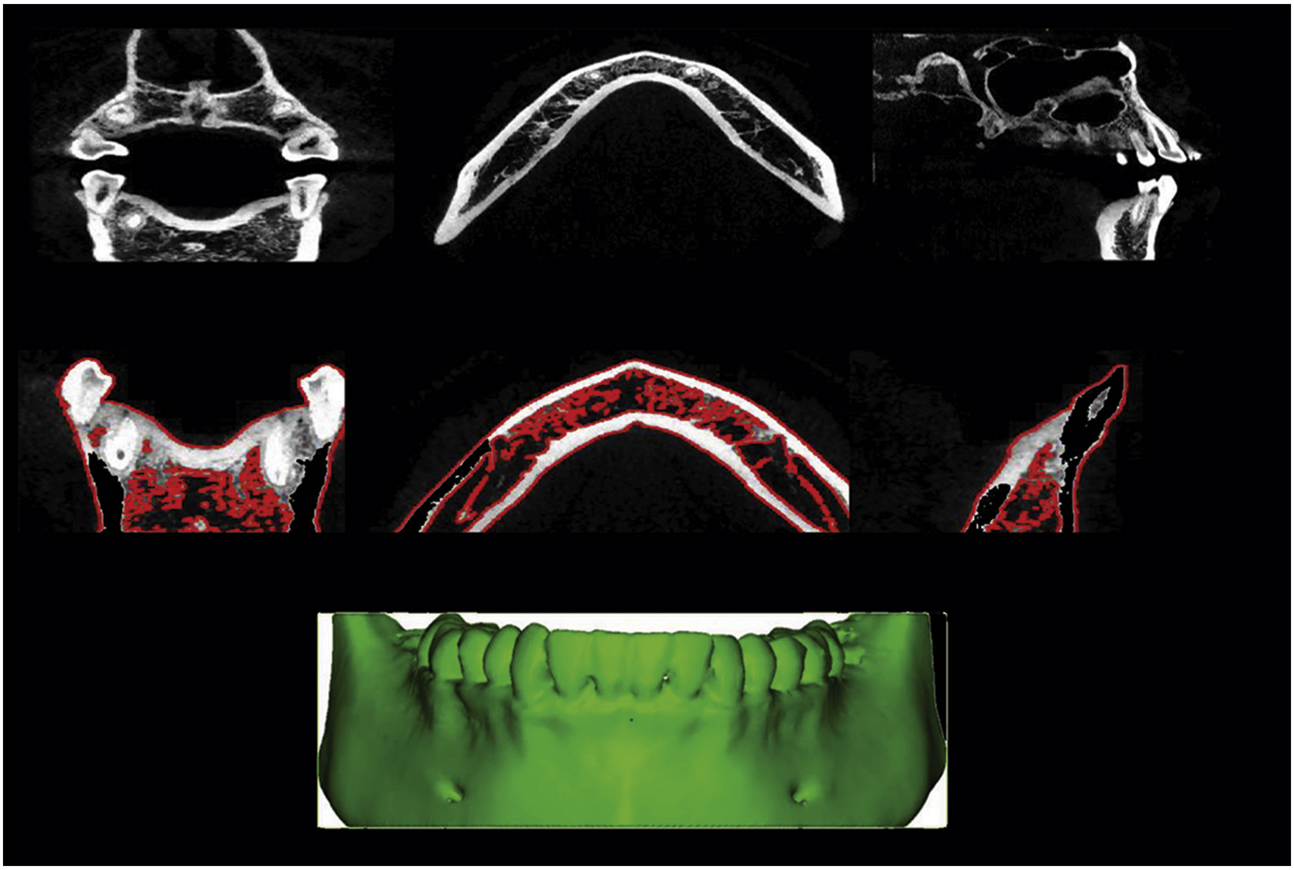

Figure 1. Segmentation and reconstruction of CBCT-derived mandibular cast. CBCT, cone beam computed tomography.

Table 1. Cast specifications

Serial No. of Casts	Technology (Total Casts Printed)	Printer	Material	Layer Resolution (μm)
1	MJ (n=4)	MJP 2500	M2R-WT	32
2		MJP 2500	M2R-CL	32
3		Objet 350	Verowhite	30
4		Objet 350	Veroclear	30
5	DLP (n=4)	Rapidshape D90 II UV XL	Dreve model	38
6		P30	P30 shera sand	50
7		Moonray S	Green dental model resin	50
8		P4 mini XL	ABS Tough	35
9	SLA (n=2)	ProX800	Accura ABS White (SL7810)	25
10		Form 2	Standard Gray resin	25
11	FDM (n=2)	In-House 1	Ossofill	30
12		In-House 2	Polywood	30
13	CJ (n=2)	ProjetPro660	Visijet PXL 1	100
14			Visijet PXL 2	200
15	LS (n=1)	In-House 3	Polyamide PA 12	120

CJ, colorjet; DLP, digital light processing; FDM, fused deposition modeling; LS, selective laser sintering; MJ, multijet; SLA, stereolithography.

intraobserver reliability. Data were analyzed with statistical software (MedCalc 16.4.2; MedCalc Software bvba). To assess interobserver and intraobserver reliability, the intraclass correlation coefficient was applied at a 95% confidence level (where <0.50=poor reliability; 0.50–0.75=moderate reliability; 0.75–0.90=good reliability; >0.90=excellent reliability).[17] The absolute mean difference and standard deviation were calculated to observe the difference between the original and printed casts. A nonpaired *t* test was performed to compare the objective accuracy of the printed casts. The *P* values were corrected following the Sidak test for multiple comparisons[18] (α=.05).

RESULTS

The objective assessment revealed excellent interobserver (0.98, *P* value=.82) and intraobserver (0.99, *P*=1.00)

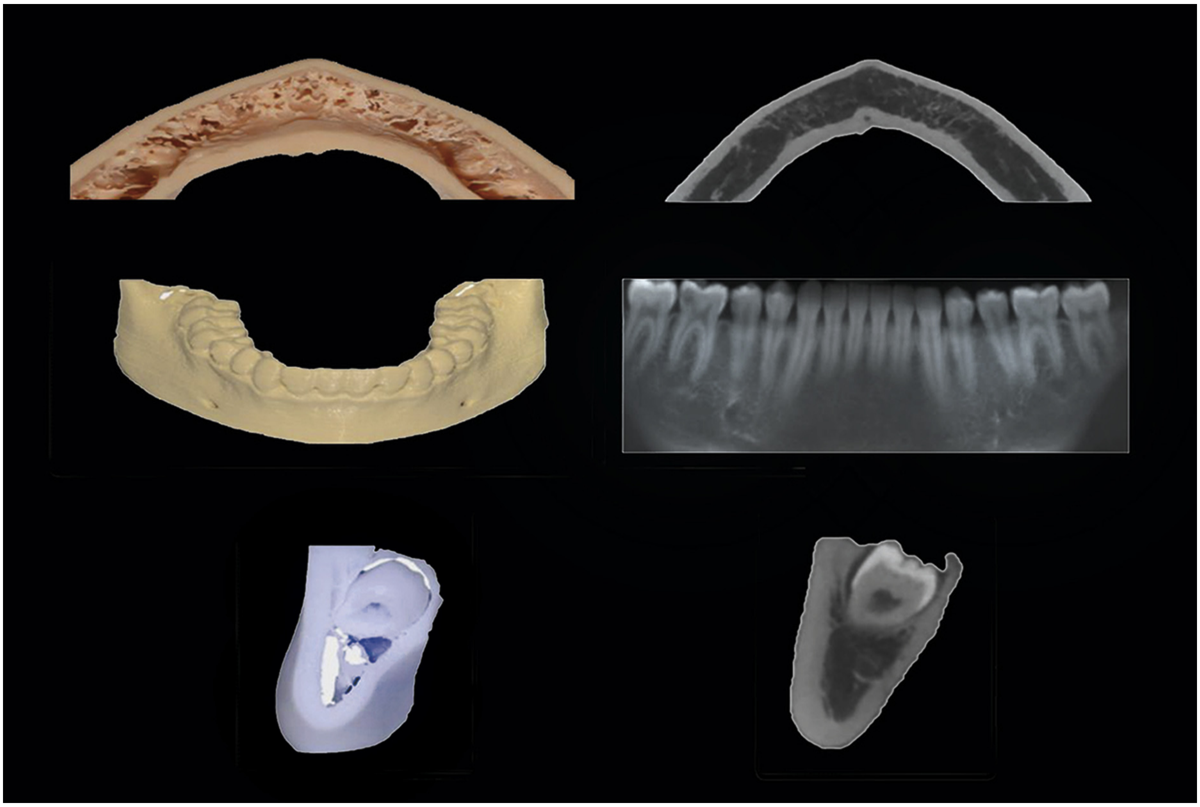

Figure 2. Cone beam computed tomography scanning of cast.

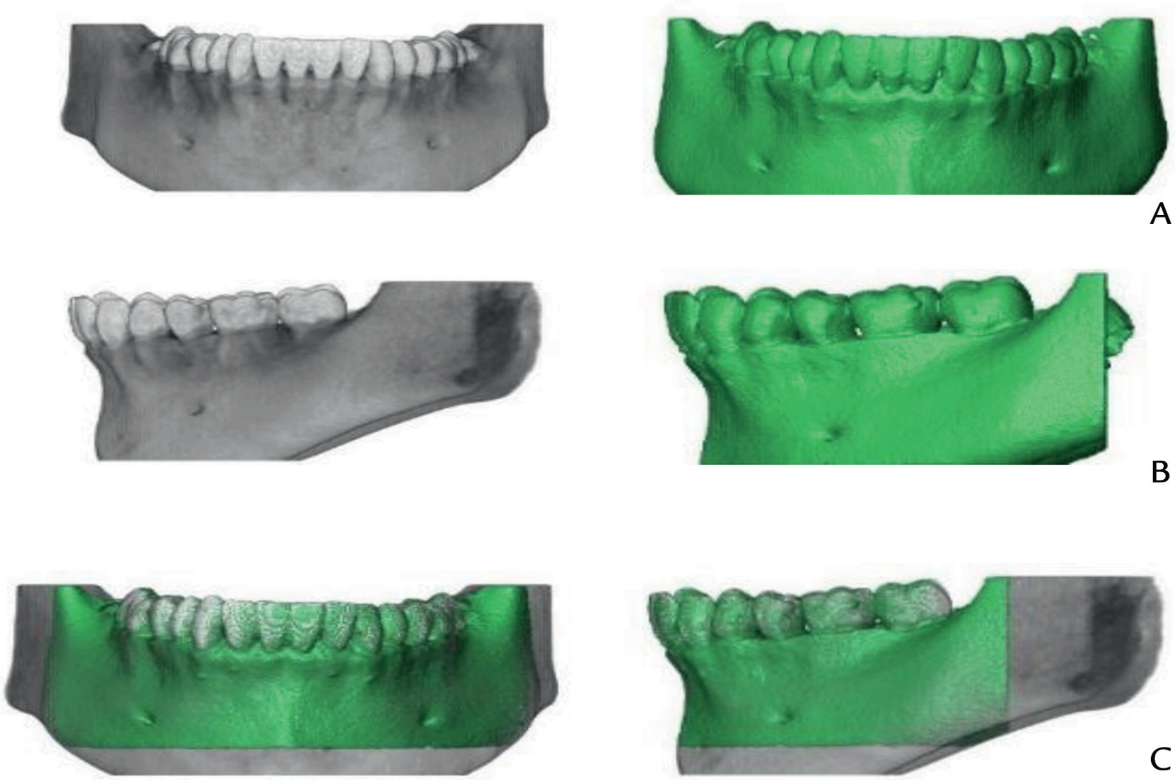

Figure 3. Steps of image registration. A, Volume editing of original DICOM data to isolate mandible followed by volume rendering. B, Volume rendering of STL file of printed casts. C, Voxel-based registration superimposing printed cast on original CBCT reference. CBCT, cone beam computed tomography; DICOM, Digital Imaging and Communications in Medicine; STL, standard tessellation language.

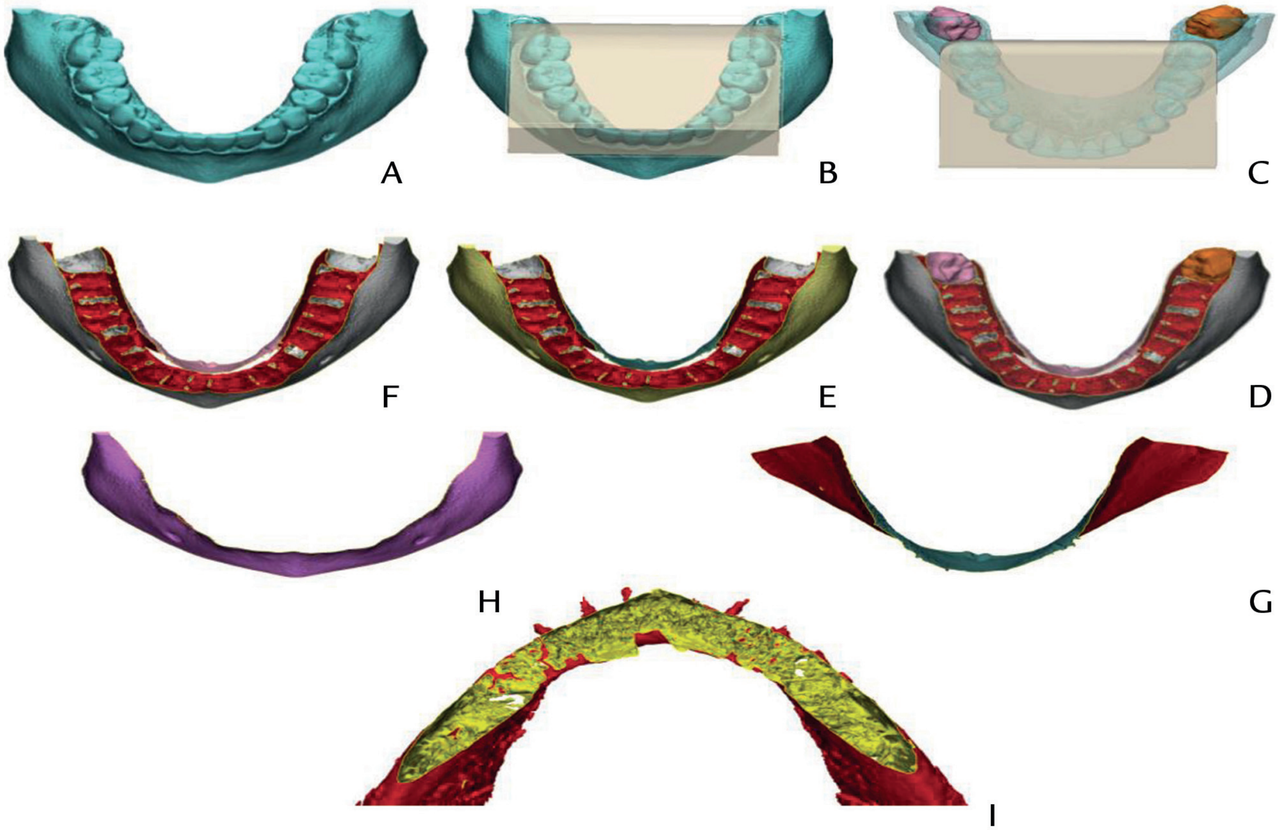

Figure 4. Surface extraction procedure. A, 3D virtual printed cast. B, Erupted tooth container. C, Impacted left and right third molar containers. D, Subtraction of erupted teeth. E, Subtraction of third molars. F, Bone container following shape of surface. G-I, Extraction of buccal, lingual, and trabecular surface.

reliability based on intraclass correlation coefficient without a significant difference among observers.

Figure 6 illustrates the accuracy of casts in relation to teeth. Cast 1 and 2 printed with MJ technology showed the least amount of error (0.06 ±0.04 mm) was associated with both erupted and impacted teeth compared with the original STL file, whereas cast 11 (FDM) showed the highest discrepancy was associated with erupted teeth (0.70 ±0.74 mm), impacted left (0.61 ±0.74 mm), and right third molars (0.55 ±0.68 mm).

Figure 7 illustrates the accuracy of casts related to replicating buccal, lingual, and trabecular surfaces. The lingual cortical surface of cast 9 (SLA) showed the least amount of error (0.04 ±0.04 mm), followed by cast 15 (LS: 0.05 ±0.04 mm), 1 (MJ: 0.06 ±0.04 mm), and 2 (MJ 0.06 ±0.05 mm). Cast 5 (DLP) showed the highest lingual surface error (0.15 ±0.12 mm). The buccal cortical surface was most accurately represented by cast 15 (LS; 0.05 ±0.06 mm), and the highest difference was observed for cast 5 (SLA) (0.15 ±0.13 mm). The trabecular surface replication of cast 2 (MJ) had the least absolute mean error (0.08 ±0.07 mm), and the highest error was associated with cast 11 (FDM: 0.43 ±0.64 mm).

When the overall combined error associated with the complete casts based on printing technology was compared, MJ showed the highest accuracy (0.6 ±0.71 mm), followed by CJ (0.67 ±0.68 mm), LS (0.67 ±0.68 mm), DLP (0.82 ±0.78 mm), and SLA (0.96 ±1.2 mm). The FDM technology (2.2 ±3.43 mm) had the highest overall absolute mean difference. However, no significant difference was observed when both individual surfaces (P=1.00), and the complete mandibular cast ($P \geq .99$) based on technology were compared.

DISCUSSION

The results of the present study showed no significant difference between the accuracy of individual surfaces and complete mandibular casts. Therefore, the null hypothesis was accepted.

Three-dimensional printed casts play a significant role in preoperative treatment planning by providing a replica of the actual craniofacial skeletal tissue and the shaping of medical devices such as fixation plates before surgery, thus enabling surgeons to familiarize themselves with patient-specific anatomy, especially in

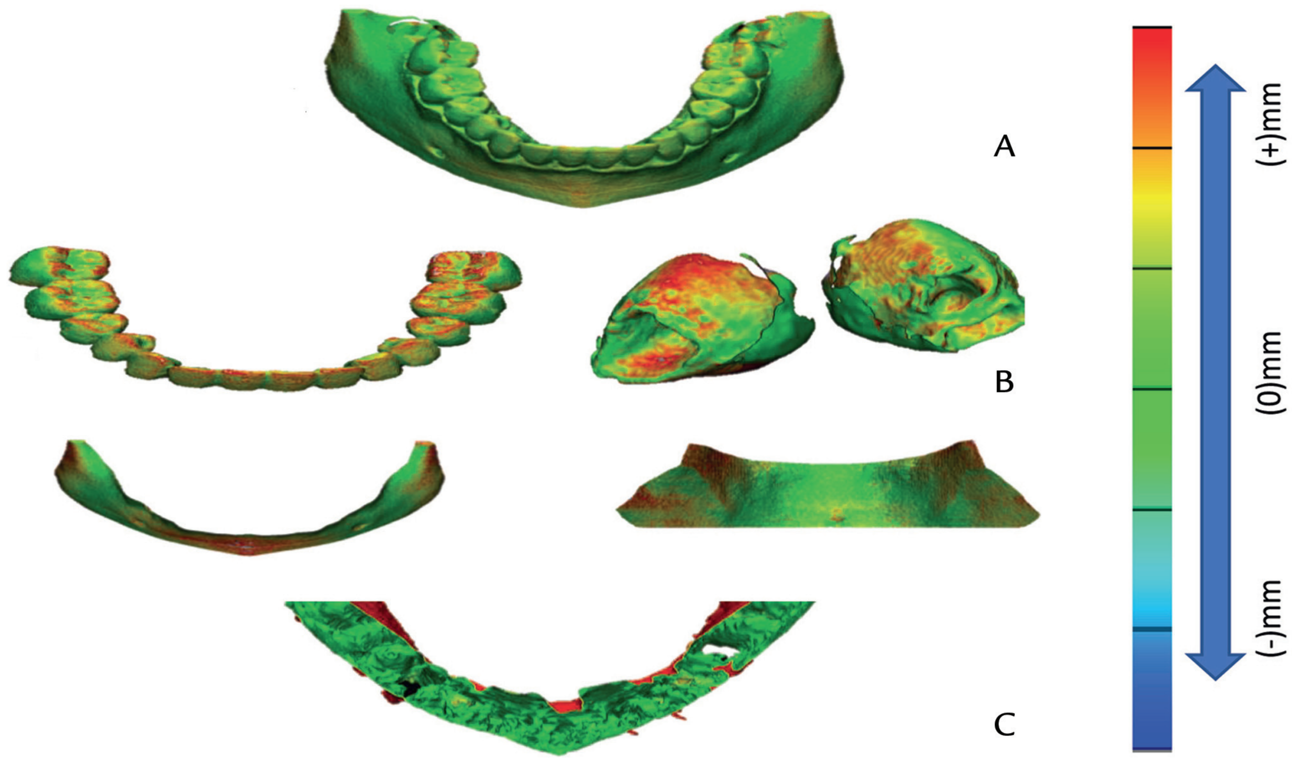

Figure 5. Part comparison analysis of superimposed original and cast STL file. A, Superimposed complete mandible. B, Color-coded difference between original and printed teeth. C, Buccal, lingual, and trabecular surface accuracy comparison. STL, standard tessellation language.

patients with atypical anatomy.[5] Additionally, practicing prosthodontic and craniomaxillofacial surgery simulations on such casts can reduce operating time and blood loss. These casts can also provide novel teaching and tools for training dental and oral and maxillofacial residents.[6]

In the present study, 6 printing technologies (MJ, DLP, SLA, FDM, CJ, and LS) were used to construct 15 mandibular casts with a combination of materials and layer resolutions to observe how precisely the anatomic structures were printed. An innovative concept of segmenting different anatomic surfaces was used to improve the accuracy and reliability of the comparison of the original with the printed cast. The findings revealed that all technologies, except the FDM-based casts, accurately represented tooth morphology and were within a clinically acceptable range of 0.25 mm.[19] However, this range was defined based on linear measurements by comparing conventional maxillary and mandibular plaster models with printed casts, and the authors are unaware of evidence for an acceptable 3-dimensional accuracy range for a cast compared with the anatomic structure. Although, no statistically significant difference was observed related to all surfaces of casts, the impact of these small differences on clinical significance is unknown.

In the present study, certain inaccuracies were also observed with both FDM-based polywood and ossofill casts. The cast acquired with the polywood material had porosities on the tooth surfaces, whereas the ossofill (polylactic acid) cast imperfectly represented the cuspal and incisal surface morphology. Furthermore, both were unable to print fine trabecular structures, possibly because of warping deformation and shrinkage during thermoplastic cooling.[20] Recent evidence has been consistent with the findings in the present study, also showing that FDM technology is inadequate for printing fine structures with reduced dimensional accuracy.[21,22]

The buccal and lingual cortical surfaces were found to be accurately depicted in all casts; however, the highest accuracy was achieved with SLA and LS casts for the lingual and buccal surfaces. PJ (multijet, colorjet) and LS technology materials had the highest overall objective accuracy. However, trabecular structures were more accurately printed with the MJ printers, which was consistent with findings from a previous study reporting the high-dimensional accuracy of LS and the better

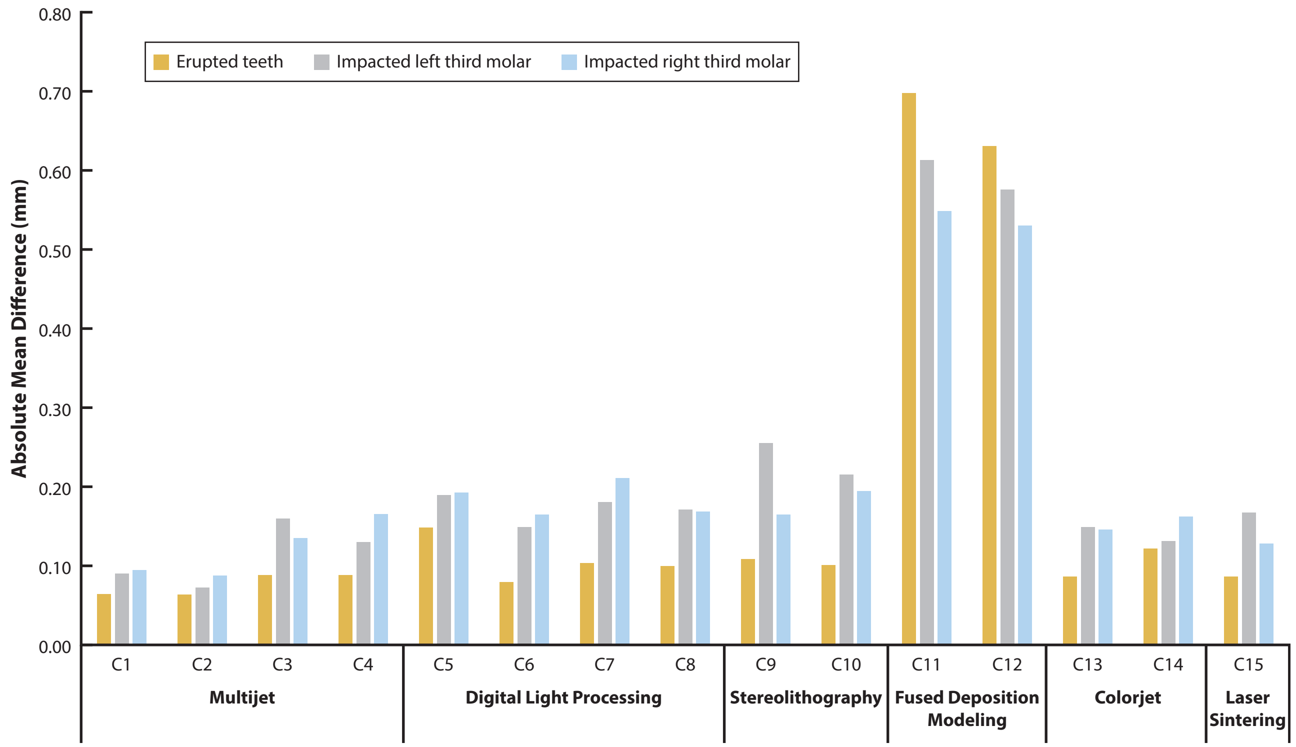

Figure 6. Absolute mean difference (mm) of tooth comparison between original virtual model and cast. C, Cast. Refer to Table 1, serial no. of models for cast specifications.

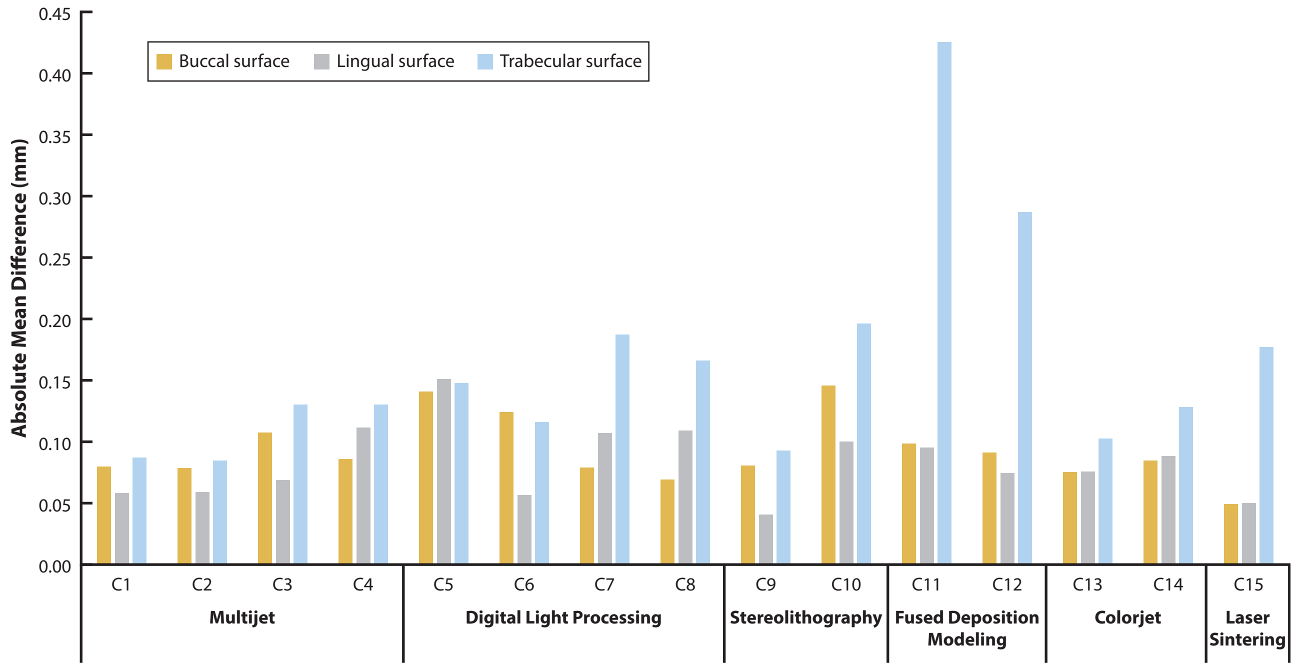

Figure 7. Absolute mean difference (mm) of buccal, lingual, and trabecular surface comparison between original virtual model and cast. C, Cast. Refer to Table 1, serial no. of models for cast specifications.

anatomic reproducibility of PJ technology.[23] As the finishing of PJ-based casts only required pressurized water for removing the support material, the postprocessing error was reduced, unlike LS, in which airborne-particle abrasion might have caused surface wear in trabecular regions.[10]

The outcomes of the present study also suggested that the accuracy of casts depended more on the combination of type of printer technology and material, rather than layer resolution. However, further studies are required to test the effect of layer resolution on the accuracy of printing casts. Also, the error associated with various CBCT devices and protocols for acquiring volumetric data and their effect on the printing accuracy should be addressed in future research. To overcome the error related to CBCT devices, the application of an accurate industrial scanner to evaluate the accuracy of printed dentomaxillofacial structures, especially trabecular architecture, and printing them separately without the need to construct a complete patient-specific cast is recommended.

The study had limitations, including that the segmentation process based on the thresholding of CBCT data required manual delineation, which was both time consuming and subjective. Further research is required to develop CBCT-friendly segmentation algorithms to allow for the detailed and accurate replication of patient-specific anatomy. Additionally, the postprocessing of casts might have introduced errors, especially for thin trabecular surfaces; therefore, improvements are required in printing technologies and materials with optimal layer resolution.

CONCLUSIONS

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

1. Overall, 3D printed casts were able to replicate skeletal and dental anatomic surfaces well, although some casts showed shortcomings in relation to depicting trabecular architecture.
2. MJ technology with Visijet M2R material was found to be the most accurate combination for replicating mandibular anatomic structures.
3. The mechanical properties of these casts need to be assessed for the purpose of drilling bone and performing dentomaxillofacial surgeries with the same tactile perceptibility as that of real bone.

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