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Craniofacial/Pediatric

Rapid-printed Three-dimensional Models for Craniomaxillofacial Trauma

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Background: Advances in surgical planning and 3-dimensional (3D) printing have benefitted the field of craniomaxillofacial surgery by allowing visualization of patient anatomy in settings of otherwise restricted surgical fields. Long 3D print times limit the usability of surgical planning workflows in acute trauma reconstruction. We sought to identify variables affecting print time and produce rapid-printed models with sufficient quality for prebending osteosynthesis plates.

Methods: Three-dimensional printing variables, including resolution, print orientation, and region of interest cropping, were optimized on a single mandibular and midface fracture model to maximize print time efficiency. Five mandibular and 5 midface fractures were printed both in the high-resolution and time-efficient protocol. Fixation plates were contoured to fit the optimized models and computed tomography scan. Distances and volumes between the fracture surface and plate were computed.

Results: High-resolution mandible models were printed in 7.47 hours and maxillae in 7.53 hours. Optimized models were printed in 0.93 and 1.07 hours, respectively. Cropping to regions of interest, rotating the model, and decreasing print resolution significantly reduced print time. The difference (optimized versus high resolution) in distance between the plate and model averaged 0.22 and 0.34 mm for mandibles and maxillae; the air space volume differed by 1.39 and 0.90 mm^3, respectively.

Conclusions: Adjusting size, resolution, and position on the printing platform allows rapid fabrication of 3D models for surgical reconstruction without sacrificing surface quality. These edits reduce printing time, enabling the implementation of 3D-printing workflows for surgical planning in acute craniomaxillofacial trauma settings. *(Plast Reconstr Surg Glob Open 2024; 12:e6308; doi: 10.1097/GOX.0000000000006308; Published online 22 November 2024.)*

INTRODUCTION

Because reconstruction in craniomaxillofacial surgery is often carried out via small incisions designed to minimize scars, it can be challenging to adequately visualize the anatomy—even when provided with appropriate preoperative computed tomography (CT) scans. The use of surgical planning and 3-dimensional (3D) printing has accelerated over the past decade and helped to circumvent such challenges.[1–3] Though this technology is used frequently in the setting of elective surgery, there are several limiting factors when it comes to trauma application. These factors include the need for videoconferencing with commercial providers or engineers for simulation of fracture reduction, long 3D print times, and delayed transit for 3D model delivery to the operating room.

Optimized workflows use in-house printing and virtual reduction services to overcome shipping or manufacturing delays.[4,5] In a study by Bergeron et al,[4] simple fracture reductions were planned in-house using open-source software, whereas more complex cases were done

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with a commercial provider using videoconference. Notably, the time to 3D print surgical aids contributed significantly to the overall duration of the workflow, with the mean ranging from around 7 hours to 26 hours. It can take 1–2 weeks to implement the presurgical plan and 3D-printed model due to transfer of data, preparation by bioengineers, need for video conference meetings, review of plan, and 3D printing and delivery.[5] In settings of emergent trauma, printing time and third-party vendor communication may constrain the surgeon's ability to utilize presurgical planning with 3D modeling for the reconstructive surgery. There are now several different software options for in-house planning which may circumvent these delays by avoiding the need for web conferencing with engineers.[6]

With the emergence of faster, refined 3D printers in the market, the workflow can be further optimized to facilitate faster delivery times. The purpose of this study is to identify and optimize the variables affecting 3D print time for mandibles and maxillae and to subsequently validate these models' clinical accuracy by testing the fit of osteosynthesis plates bent to optimized models.

METHODS

Fracture Selection

Deidentified CT scans of 5 fractures each of the midface and mandible were collected. Virtual surgical reductions were performed in a virtual reality planning environment using ImmersiveView (ImmersiveTouch, Inc., Chicago, Ill.). Fracture reduction files in the form of standard tessellation language (STL) were loaded into Meshmixer (Autodesk, San Rafael, Calif.) for preparation for 3D printing.

Print File Preparation

Files were remeshed in Meshmixer to create uniform faces. To hollow solid components of the meshes, the shell function was utilized. To crop to the region of interest (ROI), a combination of plane cut and "select" function was used. After cropping, the region was isolated using the separate shells function.

Printer and Fixed Settings

The SprintRay ProS (SprintRay, Inc., Los Angeles, Calif.) was used for 3D printing, it can print using a variety of biocompatible resin materials with a layer thickness of 50, 100, or 170 µm.[7] The SprintRay uses digital light processing 3D printing, wherein the resin layer is created and cured simultaneously via a projection of light in the desired shape. Thicker printing layers, also denoted as resolution, print faster "Die&Model2," a Food and Drug Administration (FDA)–compliant biocompatible sterilizable resin, was used. Postprocessing of the printed model is resin and manufacturer-specific, involving an isopropyl alcohol bath of 91% or higher, air drying, and ultraviolet photocuring.[8] Structural supports are removed manually and support remnants may be sanded off.

Takeaways

Question: How can the three-dimensional (3D) printing process be optimized to reduce print time and maintain clinical accuracy in urgent craniomaxillofacial trauma surgery?

Findings: Our study showed that by cropping the region of interest, adjusting model orientation, and changing resolution, 3D print times for mandibular and maxillary fractures were significantly reduced to around 55 minutes and 1.07 hours, compared with 7.47 and 8.49 hours for high-resolution models, without compromising clinical accuracy, as validated through plate fit testing.

Meaning: Optimizing 3D printing processes for surgical models—by adjusting size, resolution, and positioning—can significantly speed up production, enabling urgent surgical planning and improving patient care in acute trauma cases.

Testing Printing Variables and Optimizing Print Time

STL files were uploaded into RayWare software (SprintRay, Inc.) to assess printability and to send to the printer. At this stage, the orientation of the model on the platform in the *x*, *y*, and *z* planes and layer thickness (resolution: 50, 100, or 170 µm) are manipulable.

Each variable was independently tested with 1 mandibular and 1 maxillary fracture. For high-resolution prints, models were positioned in the SprintRay software default rotation while avoiding orientations that would place supports over the fractured ROI and compromise surface quality. Total print time, total resin volume used, and total time to edit and prepare the STL were recorded for each trial. Nonmodifiable printing variables (postprocessing times) were not included in the calculation of workflow print time.

Evaluating the Accuracy of the Optimized Protocol

The identified optimized printing protocol was applied to a total of 5 unique mandibular fractures and 5 unique maxillary fractures. All 10 of the fracture models were printed using the highest-resolution setting (50 µm) for comparison.

To validate the clinical applicability of the optimized models, osteosynthesis titanium fixation plates were bent to the optimized model surface using standard plate bending forceps. For the mandible fractures, a standard 2.0 mm locking reconstruction plate was chosen. The number of holes varied between fractures (range 6–8). For the zygomaticomaxillary complex fractures, a 1.7-mm 5-hole nonlocking L-shaped miniplate was chosen. The location of fit was determined by measurement from predetermined surface landmarks to ensure that the plate was contoured to the same anatomy for both model versions. The plates were secured to the models with museum wax, with care not to alter the relationship between plate and model. The models were scanned by i-CAT FLX cone beam CT using a voxel size of 0.3 mm. DICOM datasets were uploaded into Mimics Medical (Materialise, Leuven, Belgium) for segmentation of models and plates, then exported as STL files and uploaded into Fusion360 (Autodesk, San Rafael,

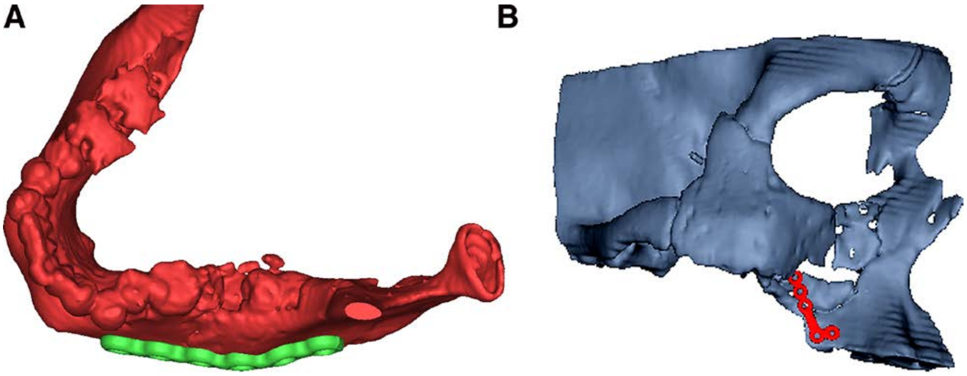

Fig. 1. Three-dimensional (3D) models after upload into Fusion360. A, 3D-printed mandible is shown in red, with plate segmentation shown in green. B, 3D-printed maxilla shown in gray, with plate segmentation shown in red.

Calif.) for volume analysis and into Mimics for distance analysis (Fig. 1).

Plate Fit Analysis

To assess the difference in plate fit on optimized versus high-resolution models, points were placed on the back side of the plate at an interval of 2 mm using Mimics Medical (Fig. 2). The measure function was used to draw a perpendicular line from the point to the model surface in the parasagittal cross section (Fig. 2). These distances were recorded, and then the absolute difference between the corresponding point distances on optimized versus unedited models were calculated.

The airspace volume between the model and the plate was taken as a second measure. The volume of a theoretical cylinder between the middle of the plate hole and the bony surface was calculated using Fusion360. The difference in the airspace volumes was calculated for each model (Fig. 3).

Statistical Analysis

To evaluate the significance between printing time and the distance between plate and model for optimized and high-resolution models, 2-sample *t* tests were performed in Excel (Microsoft Corporation, Redmond, Wash.). To assess the measure of frequency and central tendency, descriptive statistics were performed in Excel.

RESULTS

Print Time Optimization

Cropping ROI and Orientation of Models

Cropping the models to the ROI and changing the orientation of the model on the platform were some of the most pertinent editing variables affecting print time. For mandible 1, cropping to the ROI without changing the orientation on the platform reduced the print time to 6.9 from 7.44 hours (93%), and for all mandibles, to an average of 6.04 hours (2.2–7.2 hours; $P > 0.05$). Cropped models were more manipulable in orientation. This allowed for the minimization of the “z” height of the model relative to the platform, which corresponds directly to the number of print layers. Rotating the ROI to minimize the number of slices printed significantly reduced the print time to an average of 2.58 hours [2.16–2.9 hours; $P = 0.00000000629$ (34%)] for mandibles (Fig. 4). For maxillae, cropping to ROI reduced print time to 5.4 hours from 12.27 hours (44%), and when combined with removal of interior details and rotation, reached a print time of 5.2 hours (42%). [**See figure, Supplemental Digital Content 1,** which displays a quarter skull model at (A) original orientation and (B) rotated to decrease in the number of slices in the *z* dimension; C is maximally edited to ROI with interior smoothing/removal, **http://links.lww.com/PRSGO/D626**.] (**See figure, Supplemental Digital Content 2,** which displays 3D-printed zygomaticomaxillary complex with manual editing completed to remove superfluous interior details, **http://links.lww.com/PRSGO/D627**.)

Hollowing STL File

The hollowing of the model did not affect print time because it did not alter the dimensions of the model being produced. Rather, hollow models had lower resin volume, at approximately 76% (62–90) of the original used volume for mandibles (Fig. 5). Hollowing was not relevant for maxillary fractures due to the differences in anatomy.

Resolution

Changing the resolution of the print alone provided a significant reduction in printing time: for the test print of mandible 1, the 7.44 hour time was reduced to 5.1 hours (68%) at 100 μm and 3.12 hours (42%) at 170 μm. For the test print maxilla 1, the 50-μm high-resolution model printed in 12.33 hours, whereas the 100-μm print took 8.75 hours (71%) and the 170-μm print took 5.54 hours (45%). [**See figure, Supplemental Digital Content 3,** which displays impact of printer resolution, where 50 μm represents the highest resolution possible (50-μm slices) and 170 is the lowest, **http://links.lww.com/PRSGO/D628**.]

Combination of Variables

Combining the edits of ROI, orientation of print, and lowest resolution produced mandible models that printed in a mean value of 55 minutes (13%) (49–60 minutes; $P < 0.00001$) and maxillary models that printed in a mean value of 1.07 hours (12%) (0.9–1.5 hours; $P = 0.0004$)

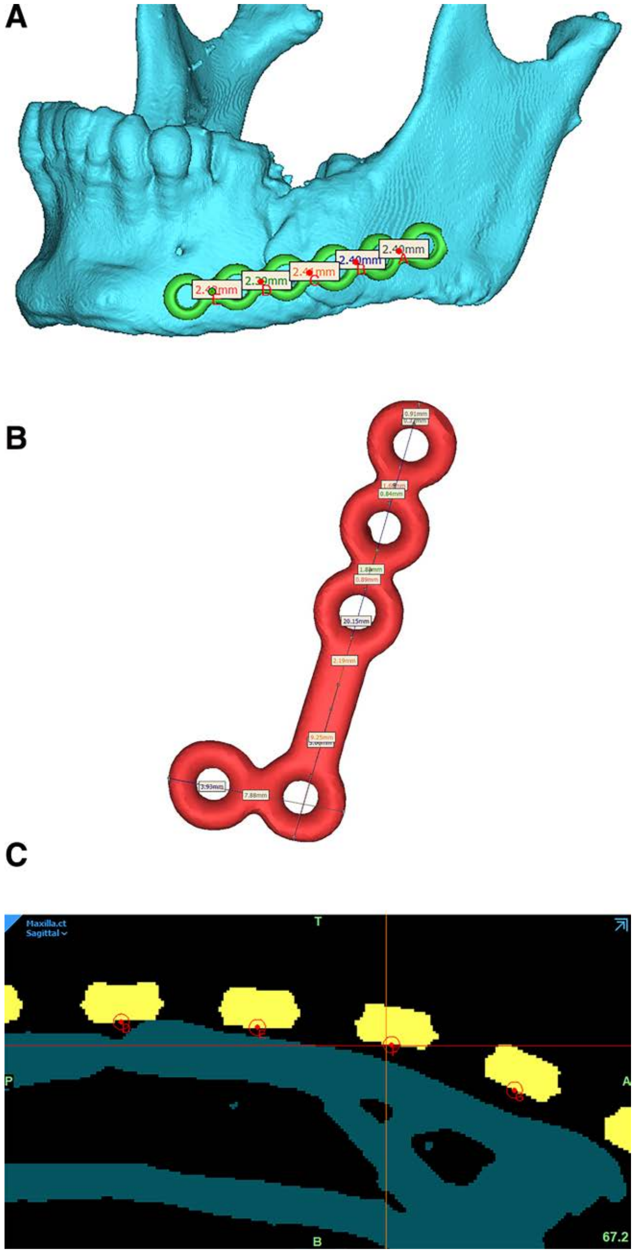

Fig. 2. 3D models of a mandible with plates, in addition to a scanned plate-mandible complex visualized using Mimics Medical (Materialise, Leuven, Belgium). A, Mandible model shown in blue, with the segmented plate shown in green. Points are placed along the length of the plate at measured distances. B, Segmented zygomaticomaxillary complex plate is shown in red with measurements delineated along the segment. C, A sagittal section of segmented mandible and plate is shown, with labeled points along the plate indicated in red.

when compared with high-resolution models printed at a mean of 7.47 and 8.49 hours, respectively. Table 1 displays the effect of these edits on printing time, and Table 2 depicts the relationship between edits and print times for all models. Figure 6 depicts the relationship between print time, resolution modifications, and the aforementioned different edits on print time for all models.

Accuracy Data

The linear distance between the mandible model and the plate differed on average between the optimized and unedited model by 0.22 mm (0.17–0.35 mm; SD, 0.13; $P > 0.05$). For maxillary models, the difference was a mean of 0.34 mm (0.16–0.66 mm; SD, 0.24 mm; $P < 0.05$). Figure 7 represents the air space distance between the plate and the edited and unedited model for mandible 1 and maxilla 1, respectively, standardized to the largest difference across the selected plate landmarks. The air space volume between the model and plate differed by a mean of 1.39 mm^3 (0.4–1.98 mm^3; SD, 0.72; $P > 0.05$) for mandibles and a mean of 0.90 mm^3 (0.33–1.19 mm^3; SD, 0.33; $P > 0.05$) for maxillae, neither of which were statistically significant. Table 2 depicts the print time as well as distances and volumes between plate and model for all 5 mandibles. (**See table, Supplemental Digital Content 4,** which displays data for maxillae 1–5 including print times and distance/air volume space analysis, **http://links.lww.com/PRSGO/D629**.)

DISCUSSION

Three-dimensional-printed models, which are available in a range of materials, including metal and biocompatible plastics, have been reported to decrease in operating time and length of hospital stay.[8–14] Furthermore, they have the potential for use in patient education as to what procedures may entail as well as anticipated postoperative outcomes. Moreover, the advent of 3D printing can help residents throughout their training better conceptualize and practice with patient anatomy and surgical planning.[14] Existing literature cites print times averaging more than 7 hours up to 24 hours.[10] Models printed in collaboration with engineers and production companies require transportation and can take several weeks to be ready for operative use.[2,4] Consequently, models are primarily used in planned elective procedures. This study identified and optimized variables affecting print time, aiming to make the workflow usable in settings of trauma while maintaining clinical usability.

There is a scarcity of data regarding the specific techniques involved in 3D printing, and a lack of objective measurements in what is primarily descriptive literature.[13,14] Our study aimed to address this gap and to further explore the variables that affect 3D printing and its implementation into clinical practice.

In-house workflows like that described by Marschall et al[15] used a similar process of virtual reduction, printing, and prebending a reconstruction plate for a case wherein the print time was about 1 hour. However, they used a prototype printer that is not accessible to other clinicians, and noted that on a commercially available printer, it would have taken about 7 hours.[15] Most studies report in-house print times in a range of more than 2 hours to as much as 27 hours, averaging about 8 hours.[4] Cost is primarily attributable to the initial purchase of a 3D printer, which can range in the thousands of dollars, as well as the cost of resin or filament, which is usually in the range of \$0.50–\$2.00 total per model for filament or 7 cents/mL for resin.[4] A model printed at full resolution without

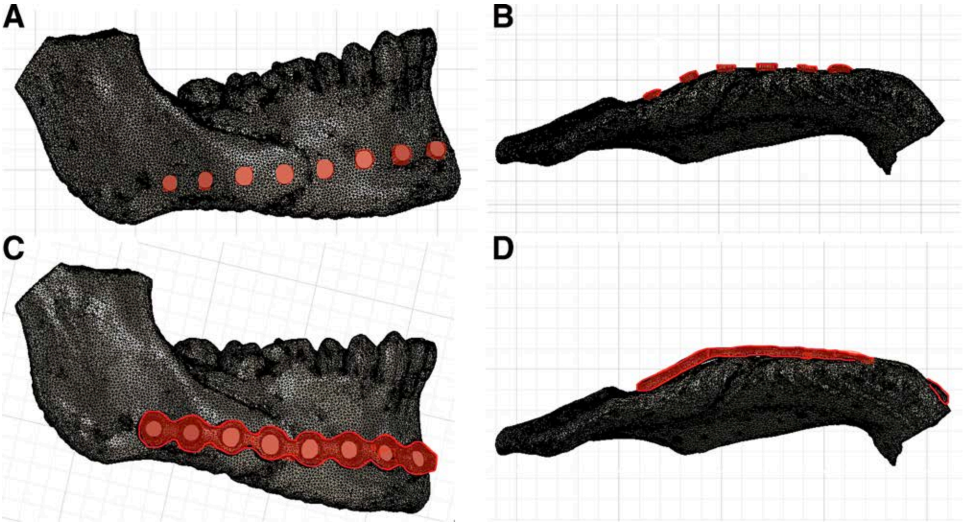

Fig. 3. 3D models of mandibles with superimposed plates visualized using Fusion360 (Autodesk, San Rafael, CA). A, Bird's-eye view of the mandible model depicts, in light gray, the volume between the plate and the resin at each hole of the reconstruction plate. B, Lateral view of the mandible model provides perspective on the cylindrical volume representing air space. C, Bird's-eye view of the mandible model with plate, volume measurements shown in light gray. D, Lateral view of the mandible model with plate.

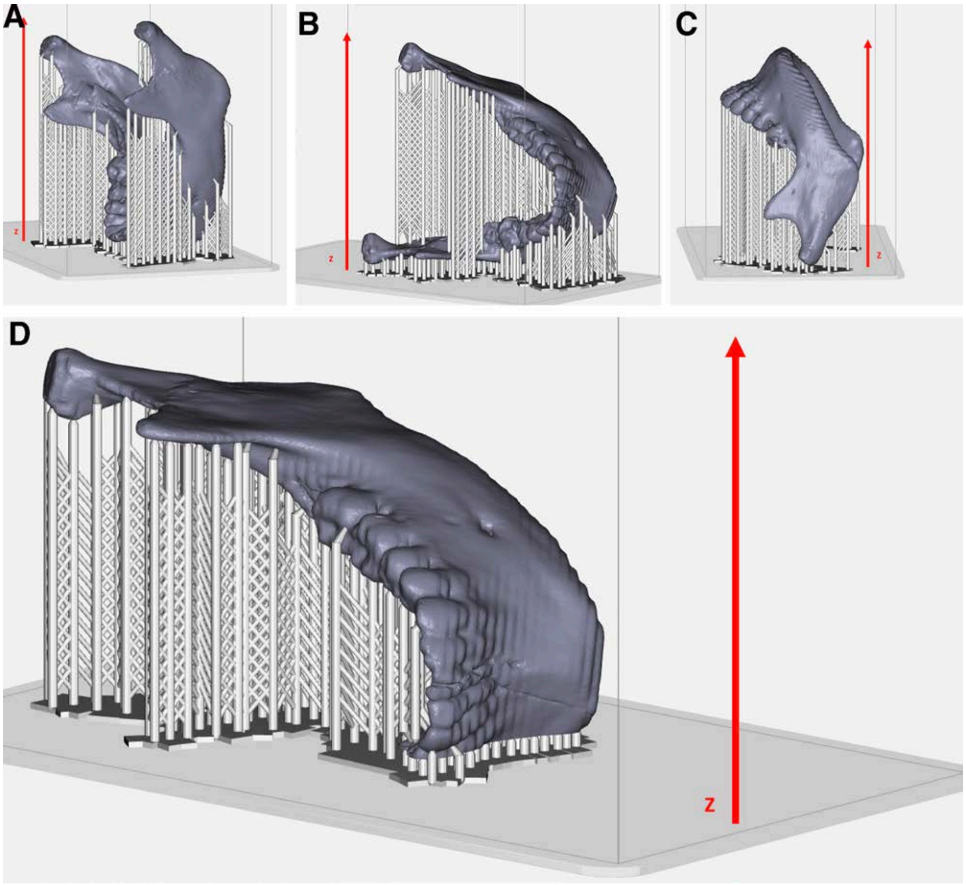

Fig. 4. Full sized and ROI-cropped 3D mandible models on printing platform. A–C, Different orientations of full-sized mandibles are displayed, from left to right, with representative supports generated and displayed. For a model with the fracture near the mandibular symphysis, the only rotation that does not sacrifice fracture surface quality is displayed in the bottom left. Notably, the model with the best surface quality for plate bending also has the largest z distance—or number of slices—to print. When the ROI is selected (D), the number of slices can be reduced without impacting the quality of the surface for plate bending.

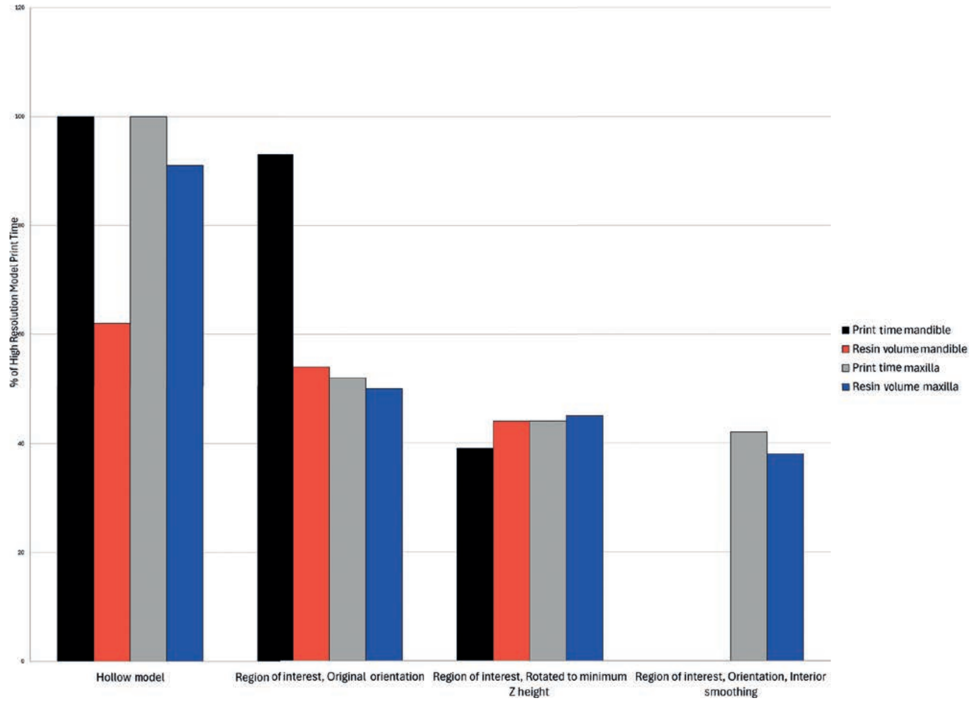

Fig. 5. Analysis of print time and resin volume for maxilla and mandible optimization.

Table 1. Alterations in Print Time Workflow Based on Manipulation of Described Variables for 1 Test Mandibular Fracture and 1 Test Maxillary Fracture

	Mandible Printing Time, h (% of Highest Resolution)	Maxilla Printing Time, h (% of Highest Resolution)
Highest resolution, 50 µm	11	12.33
Resolution, 100 µm	7.5 (68)	8.74 (71)
Lowest resolution, 170 µm	4.58 (42)	5.54 (45)
Hollow model, 50 µm	11 (100)	12.33 (100)
ROI, original orientation	10.23 (93)	6.5 (52)
ROI, rotated orientation	4.29 (39)	5.4 (44)
ROI, rotation, interior edits	*	5.2 (42)
All edits and lowest resolution	0.98 (13)	0.95 (7.7)

*Interior edits for mandible models did not make a difference in print time.

Table 2. Data for Mandibles 1–5 Including Print Times and Distance/Air Volume Space Analysis

	Original Print Time, h	Optimized Print Time, h	Δ Distance of Plate and Model, mm	Δ Air Space Volume of Plate and Model, mm^3
Mandible 01	7.44	0.98	0.03	1.74
Mandible 02	8.00	1.00	0.34	0.87
Mandible 03	7.18	0.83	0.21	1.99
Mandible 04	7.22	0.88	0.35	1.98
Mandible 05	7.50	0.97	0.18	0.41
Average	7.47	0.93 ($P < 0.0001$)	0.22	1.40

cropping would therefore cost about $6 versus $2.80 for an edited model. Several studies have looked at printing only the ROI in the context of anatomic skull defects with compression molding or orbital floor fractures for plating.[4,16–19] To our knowledge, this study is the first to report specific alterations to the printing process that can facilitate faster prints of both the mandible and maxilla in the setting of traumatic fractures. Our results identify variables that can permit the translation of the benefits of 3D printing to patients with acute injuries—in descending order of impact on print time, they are: resolution of print; cropping of model; and, if time and technical skill allow, manual removal of superfluous details. The most decisive variables affecting printing time for laser-based stereolithography are the number of slices that the printer produces: this is primarily impacted by the height of the model in the *z* dimension and the resolution—or slice thickness—that the printer is programmed to generate.[20]

The literature on 3D prints in the setting of surgery primarily assesses outcomes qualitatively, based on subjective

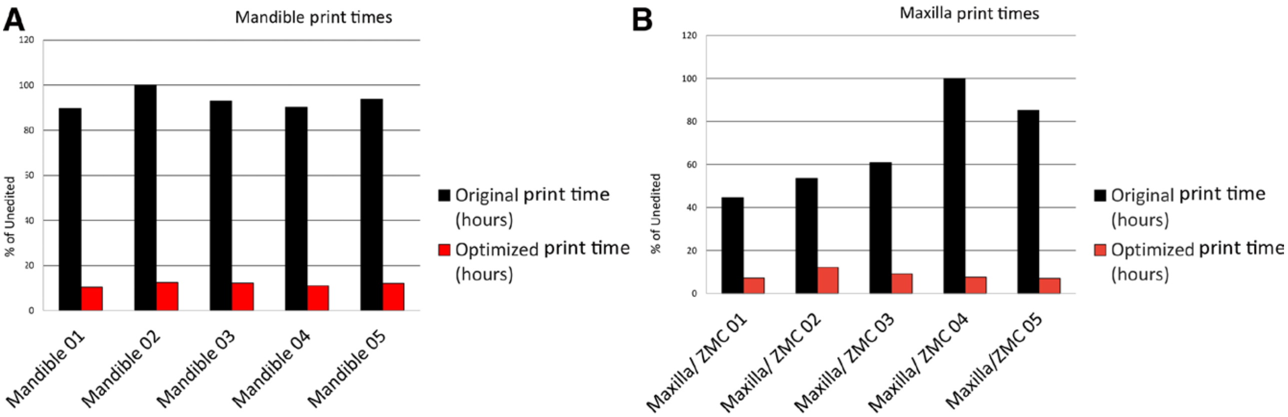

Fig. 6. Graph showing the relationship between high-resolution model print time and optimized model print time for all 5 (A) mandible models and (B) maxilla models.

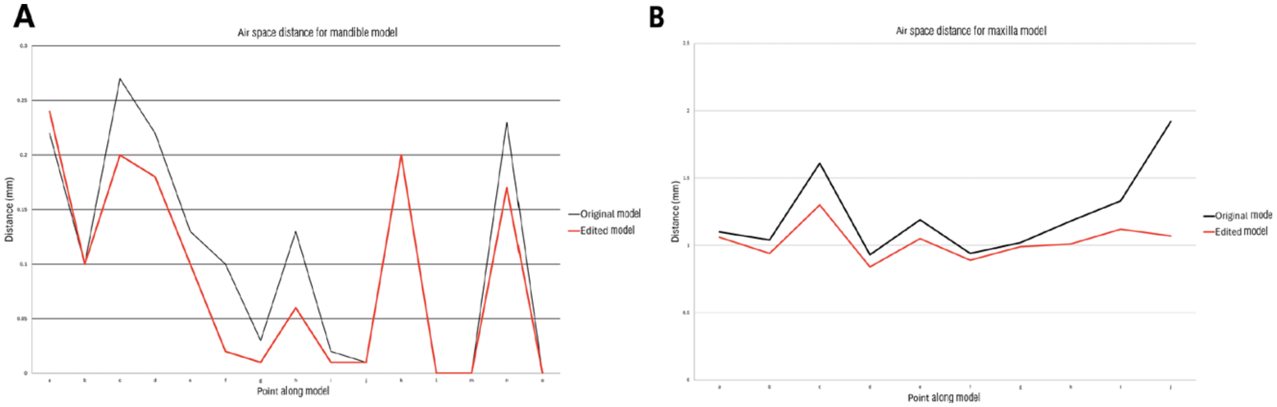

Fig. 7. Graphs showing the air space distance for (A) mandible and (B) maxillary models.

measures of plate fit, similarity, and presence/absence of postoperative complications.[15,17–19,21,22] We sought to provide quantitative analysis on the accuracy of plates that are bent using 3D printing models by measuring the air space distance and volume between bent plates and models. This allowed for quantification of the effect of changes in resolution and print quality on plate fit: plates were bent to the lowest resolution optimized models, and then affixed in turn to both the optimized and unedited models for analysis. There was no statistically significant difference in air space volume or distance for mandible models. For maxilla models, there was no statistically significant difference in air space volume, though there was for linear distance. However, this statistically significant difference was only 0.34 mm, which we consider clinically insignificant. This analysis serves to demonstrate objectively that the highest resolution, uncropped anatomical models are entirely unnecessary for the intended purpose of osteosynthesis plate bending for trauma cases. A region-cropped, lowest resolution–optimized print can provide the same anatomical reference and can be produced in a fraction of the time, opening the door for its routine usage in the trauma setting. Finally, we sought to transfer the validity of our results to the operative room, where a mandibular plate was bent using an optimized 3D-printed model using our workflow; real-life clinical results are shown postoperatively (Fig. 8).

Challenges and Limitations

Depending on the make and model of the printer used, settings can vary in adjustability. For example, Formlabs standard resins allow a minimum 100-µm resolution, though they recently released "Draft" resin that can print to 200 µm.[23] Here, the highest resolution (50 µm) versus the lowest resolution (170 µm) prints maintained the relationship between model and plate. Potentially, the resolution difference of 120 µm from a baseline 50 µm may be extrapolated to other printers, though this will need to be confirmed.

Region selection for model cropping is a quick edit that is relatively limited by the preference of the surgeon: some surgeons may prefer to retain the entire model to have a clear picture of the whole anatomy.[13] When this is not necessary, one can select only the applicable ROI required for plate bending. These modifications require more extensive communication with the surgeon to ensure that the materials necessary for operative intervention are available.

Removing the interior-most, superfluous aspects of the model is relatively technically intensive and minimally reduces print time. It was most effective in maxillae models when it allowed increased freedom of rotation that decreased the number of slices in the z dimension (**Supplementary Digital Content 1, http://links.lww.com/PRSGO/D626**). Hollowing of the model primarily reduces

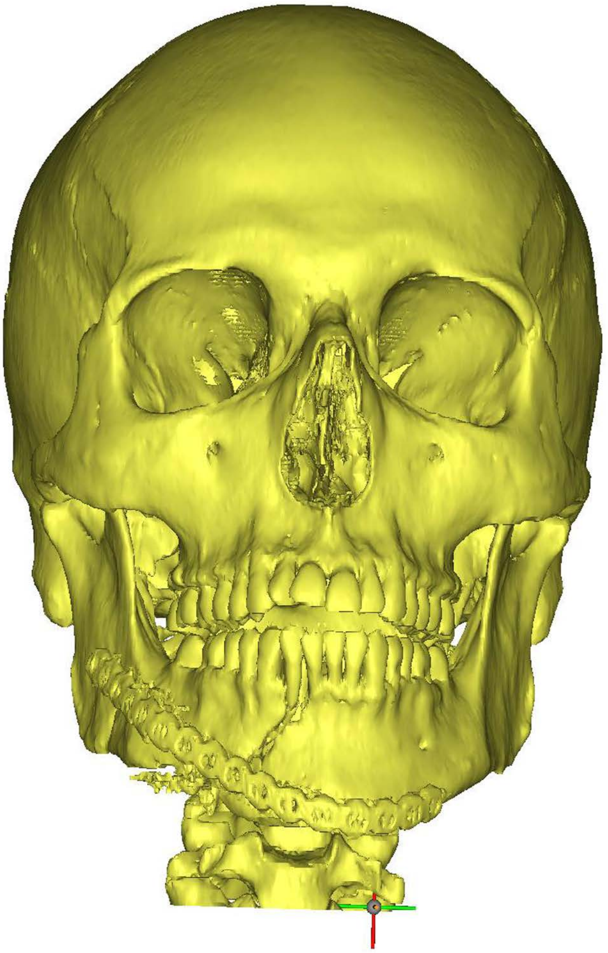

Fig. 8. Postoperative CT scan of a mandibular plate bent using an optimized 3D-printed jaw model.

the quantity of resin used. Because resin is relatively inexpensive, this may not represent an efficient use of time and has a low impact on cost savings. Although Meshmixer is not specifically FDA-approved for clinical use, existing literature has described its utility in surgical planning. Materialise Mimics is an alternative FDA-approved software that can be used to make the edits described in this article.[6]

The average time to print the optimized models in this workflow was 0.95 hours, which represents a significant decrease compared with the existing literature, which tends to range in the order of days, rather than hours, for both in-house and commercially produced models.[4] Even relatively faster print times of 8–10 hours represent a day-long process when accounting for processing times for use in the operating room.[24] Hour-long prints, as accomplished with simple edits as proposed by the workflow in this article, can allow the implementation of the presurgical planning workflow even in cases of acute trauma requiring more urgent intervention.

Future Directions

The achievable speed of 3D printing will likely continue to improve with technological advances. Already, the use of in-house 3D printers is becoming more popular in hospital settings and popularizing faster, point-of-care printing.[4,6,15,24] By continuing to optimize the variables associated with print times, we were able to remove one of the barriers to the use of surgical planning in the urgent trauma setting. It is possible that there are additional edits or settings that were not tested within the context of this study that could reduce print times further; these should be further explored and described to keep the workflow contemporary with future hardware and software updates. Reducing 3D printing time is 1 piece of the puzzle of optimizing the surgical planning workflow. Existing workflows either require sequential fracture reduction in coordination with an engineer or utilize a “mirroring” of the contralateral side to restore normal anatomy. Notably, both methods used a 3D printing model for plate bending.[14] Thus, a significant contributor to prolonged lead times in production is the need for coordination between surgeons and engineers to create the surgical plan. Future research should seek to create a cohesive surgical workflow that allows for prompt, surgeon-steered algorithms that may be implemented in the setting of trauma cases.

CONCLUSIONS

Our findings indicate that 3D models can be rapidly fabricated for use in surgical reconstruction by adjusting size, resolution, and position of the model on the printing platform without sacrificing surface quality for plate bending in the OR. These basic alterations, including cropping to ROI, decreasing print resolution, and rotating the model on the printing platform, can reduce printing time and implement the virtual surgical planning and 3D printing workflow much more readily in the time-sensitive setting of acute craniomaxillofacial trauma.

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DISCLOSURE

The authors have no financial interest to declare in relation to the content of this article.

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